DOCTOR OF PHILOSOPHY

An investigation into the influence of buildability factors on productivity of in situ reinforced concrete construction

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An Investigation into the Influence of Buildability Factors on Productivity of *in situ* Reinforced Concrete Construction

by

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To My Wife

Lama

Whose without her Encouragement and Patience, this Project could not have been possible.

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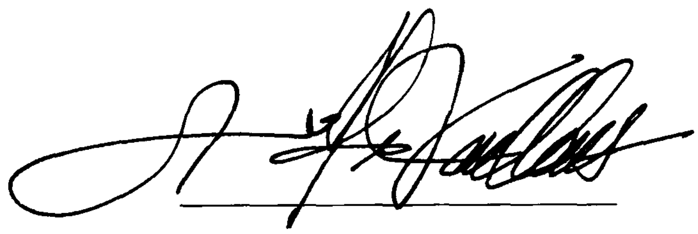
Declaration

I hereby declare that this Thesis has been compiled by me, that it is a record of work completed by me, and that it has not previously been accepted for a higher Degree at this University or any other Institution of learning.



Abdulaziz Mohammad Jarkas

Certificate

This is to certify that ***Abdulaziz Mohammad Jarkas*** *has done this Research under my supervision, and that he has fulfilled the conditions of Ordinance 39 of The University of Dundee, so that he is qualified to submit for the Degree of Doctor of Philosophy.*

R. Malcolm W. Horner

Professor of Construction Engineering & Management

Abstract

Construction productivity is one of the most frequently researched topics due to its importance to the viability of the industry. It is regarded as a true reflection of the efficiency and economic success of the operations.

Despite the plethora of research into construction productivity reported over the years, a thorough examination of the literature revealed a dearth of research into the influence of buildability factors, i.e. design variables, on the labour productivity of one of the most important materials in the construction industry; *in situ* reinforced concrete.

According to the Construction Industry Research and Information Association (CIRIA), buildability is defined as "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building". Apart from the Singaporean Buildable Design Appraisal System (BDAS), which suffers from major shortcomings, to date, no comprehensive study was conducted to investigate and quantify the effects and relative influence of architectural and structural buildability factors on the labour productivity of *in situ* reinforced concrete buildings. In this project, the major buildability factors hypothesised to influence the labour productivity of the main trades, i.e. formwork, reinforcing steel fixing, concreting and finishing, included grid patterns of footings and columns, type of structural framing system, geometry and dimensions of elements, height of floors, the degree of design rationalisation, standardisation and repetition of elements, reinforcing steel quantity and diameters, location and congestion of reinforcement, volume and workability of concrete as well as surface finish.

In addition, and due to its importance to the productivity of the construction industry, the effect of the learning curve theory has been the subject of several previous studies. However, a comprehensive investigation of the impact of the learning phenomenon on the major trades associated with *in situ* reinforced concrete buildings has not been carried out.

The raw data were collected from thirty-nine different construction sites in the State of Kuwait, using specifically designed data collection forms for a total period of nineteen months. In order to triangulate

the results, productivity data were collected and analysed at both levels; macro and micro. Since several sites were monitored simultaneously, the intermittent observation technique was selected to form the basis for the observation method.

Several relevant buildability factors impact the labour productivity simultaneously. Therefore, to isolate the net effects and quantify the relative influence of these factors on labour productivity, linear regression was used for the statistical analysis throughout this research project.

As a result, it was possible to quantify the relationship between labour productivity and the following buildability factors: a) footings and columns grid pattern; b) formwork area; c) variability of elements size; d) geometry of elements, i.e. circular versus rectangular columns, curved versus linear beams, non-rectangular versus rectangular slabs, and number of angles around the perimeter of slabs and walls; e) number of beams used to support the floor area; f) number of beam intersections in the framing system; g) dimension of elements; h) reinforcing steel bar diameter; i) quantity of reinforcement fixed; j) location and congestion of reinforcement; k) volume and workability of concrete; l) height of floors above the ground level; and m) power- trowelled floor finish.

The applicability of learning curve theory to formwork, reinforcing steel fixing and pumped concrete was investigated using the unit straight-line model. Due to the negative impact of height on pumped concrete productivity, the effect of learning on this trade could not be determined. On the other hand, the effect of the learning phenomenon on formwork and reinforcing steel fixing labour productivity was insignificant suggesting no potential context for the theory to be used as a useful tool to quantify the productivity improvement, allocate resources or schedule activity durations.

This research project has quantified the relationship between the principal design characteristics of *in situ* reinforced concrete construction and labour productivity of the various trades involved. It can provide practical guidance to architects and structural designers who seek to optimise their designs. In addition, it can give a feedback on how well the designed building considers the requirements of the basic buildability principles and provides for tangible consequences of their design decisions on the construction labour productivity.

Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BDAS	Buildable Design Appraisal System
BRS	Building Research Station
BS	British Standards
CIDB	Construction Industry Development Board
CII	Construction Industry Institute
CIRIA	Construction Industry Research and Information Association
CMRU	Construction Management Research Unit
DB	Design and Build
DBOT	Design, Build, Operate and Transfer
GDP	Gross Domestic Product
GRP	Glass Reinforced Plastics
mh	man-hours
OEEC	Organisation for European Economic Cooperation
PFP	Partial Factor Productivity
RICS	Royal Institute of Chartered Surveyors
TFP	Total Factor Productivity
VIF	Variance Inflation Factor

Notations

A	Area
AD	Average Depth
ALO	Axes Layout
APA	Average Slab Panel Area - Formwork
ASA	Average Shutter Area - Formwork
AVA	Average Panel Area - Reinforcement
AW	Average Width
BFR	Beam Floor Ratio
CBDia	Characteristic Bar Diameter
CGeom	Column Geometry
CSDia	Characteristic Stirrup Diameter
D	Depth
FA	Floor Area
H	Height
HWRK	High Concrete Workability
LLoc	Layer Location
LWRK	Low Concrete Workability
MWRK	Medium Concrete Workability
NJ	Number of Joints (Intersections) in Beams
NOM	Number of Trowelling Machines
P	Labour Productivity
PCB	Percentage of Curved Beams
PCC	Percentage of Circular Columns
PNRP	Percentage of Non-Rectangular Slab Panels - Formwork
PRCB	Percentage of Reinforcement in Curved Beams
PSCC	Percentage of Steel in Circular Columns
PSNP	Percentage of Steel in Non-Rectangular Panels
Q	Quantity of Reinforcement
RF	Repetition Factor
SA	Shutter Area
SCR	Steel Congestion Ratio

SDia	Stirrup Diameter
T	Thickness
TNJ	Total Number of Joints (Intersections) in Beams
TQ	Total Quantity of Reinforcement
TSA	Total Shutter Area - Formwork
V	Volume of Concrete
VOB	Variability of Beams (Total Number of Different Sizes of Beams)
VOC	Variability of Columns (Total Number of Different Sizes of Columns)
VOF	Variability of Footings (Total Number of Different Sizes of Footings)
W	Width

Chapter One

Introduction

1.1 Research Background

Construction is the world's largest and most challenging industry [112]. On average, it contributes one-half of the gross capital and 3 to 8% of the Gross Domestic Product (GDP) in most countries [12]. Consequently, improvement in the productivity of this industry would translate into national economic prosperity, lower production cost, higher demands for building construction, thus, higher wages and ultimately, higher standards of living.

Productivity, in its most general term, is an economic measure defined as a ratio of output to input. Depending upon the objectives of measurement, numerous definitions and mathematical expressions are encountered [2,7,12,26,33,43,51,66,86]. Since productivity is defined as a ratio of output to input, construction productivity can be regarded as a measure of outputs which are obtained by a combination of inputs. In view of this, two measures of construction productivity emerge; total factor productivity, where all outputs and inputs are considered, and partial or single factor productivity, where outputs and partial or single selected inputs are considered.

The advantages of partial or single factor productivity are many. By focusing on a selected factor, the measurement process becomes easier and more controllable. In addition, the complex nature of the construction industry and the interaction of its activities, make the partial or single factor productivity the popular option due to the flexibility of implementing effective control systems to monitor each input separately.

Since labour constitutes a large part of the construction cost, and labour hours are more susceptible to the influence of other factors such as, buildability, management, construction method and weather, than materials or equipment, this research focuses on the single factor productivity, namely, the labour productivity.

Several factors affect labour productivity but, buildability is amongst the most important [1,17,25,50,51,53,74,115]. Buildability, as defined by the Construction Industry Research and Information Association (CIRIA), is "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building" [23].

Based on this definition, we may conclude that buildability, in its broad term, is a function of the various design disciplines of a building, i.e. architectural, structural, mechanical, electrical and finishes, the inter-relationships amongst those disciplines and their effects upon the operational sequences. We may therefore think of "total" factor buildability as representing the overall influence of the combined buildabilities of such design disciplines whereas, "partial" factor buildability represents the impact of a single or selected design disciplines on the construction process.

One of the most important available construction materials is reinforced concrete. It is used as the structural component for almost all types, sizes and heights of structures. Low and high-rise buildings, bridges, dams, towers, pavements, tunnels, water and wastewater treatment plants are prime examples. Due to the importance of this material to the construction industry, this research focuses on the effects of partial factor buildability, i.e. architectural and structural designs, on the labour productivity of major elements and building frames of *in situ* reinforced concrete construction.

Buildable design leads to higher labour productivity and lower construction cost [17,25,74,78,115]. Several previous studies investigated the influence of buildability on the construction process [4,17,21,25,34,40,41,50,74,78,115]. Apart from the Buildable Design Appraisal System (BDAS), developed by the Construction Industry Development Board (CIDB) of Singapore [21], which suffers from major shortcomings, to date, and despite the importance of this material to the construction industry, no comprehensive study was conducted to investigate and quantify the effects of architectural and structural design variables on the construction labour productivity of *in situ* reinforced concrete buildings.

Major buildability factors influencing the labour productivity of the main trades in *in situ* reinforced concrete buildings, i.e. formwork, reinforcing steel fixing, concreting and finishing, include grid patterns of footings and columns [8], type of structural framing system [21,34,91], geometry and dimensions of elements [4,34,50,99,100], height of floors [11,34], the degree of design rationalisation, standardisation and repetition of elements [8,24,25,34,40,44,64,73,81,87,99,104], reinforcing steel quantity and diameters [4,34,50], location and congestion of reinforcement [4,50,76,94], volume of concrete cast, surface finish and the specified concrete workability [11,90,99].

Because of its importance to the construction industry, especially to the productivity of the process, the effect of learning curve theory on labour productivity has been the subject of several previous investigations [25,27,28,30,37,82,110,111]. However, a comprehensive investigation of the impact of learning on the major trades associated with *in situ* reinforced concrete buildings, i.e. formwork, reinforcing steel fixing and concreting, has not been carried out.

Productivity data will be collected and analysed at the macro and micro-levels. The basic difference between the two levels stems from the work sequence and labour inputs. At the macro-level, the observed input composes of the total productive time used to achieve the total physical output of the monitored activity, i.e. contributory and direct inputs [4,18,50,103]. At the micro-level however, only effective or direct productive input applied to achieve the output of an observed individual element within the activity is monitored.

Investigating and quantifying the effects and relative influence of partial buildability factors, i.e. architectural and structural, on the labour productivity of buildings at the macro and micro-levels, as well as exploring the applicability of the learning phenomenon to this type of construction, are the focal points of this research project.

1.2 Problem Statement

Reinforced concrete is one of the most important available materials in the construction industry. Despite the plethora of research into construction labour productivity reported over the years, a thorough examination of the literature revealed a dearth of research into the influence of buildability factors, i.e. design variables, on the labour productivity associated with *in situ* reinforced concrete construction.

As was previously indicated, buildability is affected by many design variables. The impacts and relative influence of such variables on labour productivity have yet to be investigated, quantified and combined in a single research project. In addition, the applicability of learning curve theory to the major trades of this type of construction has not been fully addressed or asserted.

Several buildability factors may impact the labour productivity simultaneously. The total effect on labour productivity will be the sum of the effects of all relevant factors. Since it is not possible to measure the effect of each factor separately, it becomes necessary to collect a large volume of data and apply the appropriate statistical techniques to determine the influence of each.

Buildability factors such as, design rationalisation, standardisation and repetition, when applicable, would include quantitative values to be directly applied in the design phase. The result of this investigation gives architects and structural designers feedback on how well their designs take account of the requirements of the basic buildability principles. It will provide guidance on how buildability can be optimised.

1.3 Research Objectives

The primary objectives of this research project are summarised as follows:

1. To identify the major buildability factors influencing labour productivity of the main trades involved in *in situ* reinforced concrete buildings, namely, formwork, reinforcing steel fixing, concreting and finishing.
2. To quantify the impacts and relative influence of such partial buildability factors on the labour productivity of *in situ* reinforced concrete trades.
3. To investigate the applicability of learning curve theory to recurring activities of formwork, reinforcing steel fixing and concreting.

4. To provide practical guidance on specific buildability knowledge and feedback on how well the designed building considers the requirements of the basic buildability principles to *in situ* reinforced concrete designers.

1.4 Research Methodology

To accomplish the objectives of this research project, several steps were carefully thought out and implemented. The major steps in the study are summarised below:

1.4.1 Literature Review

The literature review consisted of a thorough examination of publications dealing with topics related to this research. Such publications included conference proceedings, refereed articles, textbooks, codes of design practice, guides and construction references, PhD and MSc theses. The objectives of the literature review were twofold: first, to develop an understanding of the related research that had been previously conducted and the progress developed in this area; and second, to identify the major shortcomings of previous research as well as major gaps in knowledge in order to form the basis for this study.

1.4.2 Development of Research Hypotheses

The main objective of this step was to design the investigation plan. The first step was to identify the relevant buildability factors influencing the labour productivity of each investigated trade. The hypothesised effects of such factors were based upon previous research, examination, site experience, and interviews with site management and gang members. Once the potential buildability factors were identified, and before initiating the data collection phase, the analysis plan was drafted so that data would be collected and analysed with specific hypotheses in mind.

1.4.3 Data Collection

Based upon the analysis plan, the data collection phase was initiated. Several construction sites were monitored and data were collected at the two levels; macro and micro. As was previously explained, at the micro-level observation, only effective or direct productive input used to achieve the output of an observed individual element within the activity is monitored. Therefore, contributory inputs such as, setting-out, reading plans and identifying element locations is of negligible influence on micro-level productivities. The observed activities were foundations; isolated and raft types, ground beams, ground slabs, columns and walls, and suspended floors, i.e. beams and slabs.

The purpose of collecting productivity data at the micro-level in addition to the macro-level was to further understand the overall phenomena and patterns emerging from the macro-level observation of the activity, and to maximise the number of productivity data points.

Since several construction sites were under observation, the intermittent observation technique was employed to collect the required data. Productive labour inputs were collected in a systematic and consistent way using pre-designed forms, screened for possible errors or outliers, and partitioned according to related trades, activities and elements. The collected data were stored in spreadsheets for subsequent analysis.

1.4.4 Data Analysis

Data were analysed using the least squares method, i.e. linear regression. Simple and multiple regression models were developed using labour productivity as the dependent variable and buildability factors as independent variables. The unique effect of each factor on labour productivity was quantified, and when several factors impact the labour productivity simultaneously, the relative influence of such factors was determined using standardised regression coefficients.

The applicability of learning curve theory to formwork, reinforcing steel fixing and concreting trades was investigated using the unit straight-line model. Collected data were transformed into natural logarithmic values and the influence on labour productivity due to learning was quantified by investigating the change in labour inputs, i.e. man-hours, as the floor or cycle number increased within the observed buildings.

Based on several previous productivity studies [17,25,50,65,74,79,103,114,115], a significance level of 0.050, i.e. 95% confidence level, was selected as an acceptable measure of the reliability of statistical inferences, and was used throughout this research project.

1.4.5 Evaluation of Findings and Discussion of Results

The objectives of this phase were to interpret and evaluate the results obtained from this investigation, and determine how well the findings fit within the existing body of knowledge. Patterns, common features and significance of findings were carefully evaluated and checked for consistency, and their practical implementations within the industry were highlighted.

1.4.6 Major Conclusions and Recommendations for Further Research

The final step involved a summary of the outcome of this project. Major conclusions were presented for each investigated trade and the shortcomings of this research were expressed. A summary of the contributions of this study was followed, and recommendations for further work in the related areas were highlighted.

1.5 Thesis Structure

This thesis contains eleven chapters. Chapters two to ten begin with an introduction highlighting the main objectives and end with a summary of main conclusions. Chapter eleven presents the major conclusions, provides a summary of the research contributions, and ends with a list of suggested recommendations for further research.

Chapter Two presents a literature review on the importance and advantages of reinforced concrete as a construction material. The various buildability factors influencing the major trades associated with reinforced concrete construction, i.e. formwork, reinforcing steel, concreting and finishing are discussed. The concepts and several definitions of buildability and labour productivity are highlighted. The only available buildability appraisal tool to date, the "Buildable Design Appraisal System", is introduced and discussed. The techniques used in measuring labour productivity are discussed and the rationale for the adopted data collection method is presented. Finally, the learning curve concept, theory and basic available models are reviewed and discussed. Chapter two seeks to develop an understanding of the related research that has been previously conducted and to identify its major shortcomings and major gaps in knowledge as a starting point for this research project.

Chapter Three develops the philosophy of the concept underlying the data analysis phase. It illustrates the methodology employed in manipulating the collected productivity data of the investigated trades, i.e. formwork, reinforcing steel fixing, concreting and finishing, and highlights the procedure used in screening and partitioning the data according to the research objectives. It expresses the buildability factors hypothesised to impact the labour productivity of each trade. The logic behind the hypothesised effect of each factor is explained and the various methods employed to quantify the outputs of the observed activities clarified. The basis for investigating the effect of learning curve theory on the labour productivity of the relevant activities is also presented.

Chapter Four presents the data collection methodology employed in this research. Pre-designed data collection forms are outlined, and the methods of construction and sites observation are illustrated. The efficient frequency for data collection is determined, and the coding system used in this research is explained.

The main objective of **Chapter Five** is to illustrate the methodology employed in analysing the collected productivity data of the various investigated trades. Statistical methods and techniques are reviewed, and the various developed regression models for the relevant observed activities within the monitored trades are presented.

The analysis of the influence of buildability factors, i.e. design variables, on the labour productivity of formwork, reinforcing steel fixing, concreting and finishing, as well as the applicability of learning curve theory to *in situ* reinforced concrete buildings are presented in **Chapters Six, Seven, Eight and Nine** respectively. The unique effects, directions and relative influence of the relevant factors on labour productivity of the investigated trades, and the applicability of learning curve theory to this type of construction are determined, quantified and presented.

The main objectives of **Chapter Ten** are to discuss and compare the findings of this study with previous research, correlate them with the existing body of basic buildability principles discussed in chapter two, and to suggest their practical implementation within the *in situ* reinforced concrete construction industry.

Finally, the major conclusions and research contributions are presented in **Chapter Eleven**, together with a list of recommendations for further research.

1.6 Summary

This chapter laid the foundations for this study. It introduced the research background and problem. The primary objectives of this research were presented, the employed methodology was briefly described and the thesis was outlined.

Chapter Two

Literature Review

2.1 Introduction

Labour productivity has been the subject of numerous research projects. Many authors focused on working methods in order to understand the root cause of low productivity, and therefore significant improvement has been achieved due to methods enhancement. Other research investigated areas such as efficient and effective management, labour motivation, loss of productive time and contract procurement methods.

This chapter starts with highlighting the advantages and importance of reinforced concrete material in the construction industry, and introduces its major trades. The various utilised formwork materials, specifications of reinforcing steel bars and concreting methods are presented and discussed. The primary objectives of this chapter are to critically review buildability and productivity, identify factors influencing each concept and establish the relationship between them. Finally, the learning curve theory and its applicability within the construction industry is reviewed and discussed.

2.2 Advantages of Reinforced Concrete

One of the most important available construction materials is reinforced concrete. It is used for almost all types, sizes and heights of structures. Low and high-rise buildings, bridges, pavements, walls, dams, towers, tunnels, water and wastewater treatment facilities are prime examples.

The success of this universal construction material is attributed to the following characteristics [46,69]:

a) considerable and relatively high compressive strength as compared to other materials;

b) long service life coupled with low maintenance cost;

c) better resistance to fire and heat than other "traditional" materials such as steel and masonry;

d) most suitable construction material when water is present;

e) high rigidity and minimum apparent deflection;

f) its ability to be cast into variety of shapes ranging from simple flat surface to complex shells and hybrids;

g) lower grade of skilled labour is required as compared to other materials, especially structural steel; and

h) it is the most economical material available for sub-structural elements such as footings, piers and basement walls

However, as with all construction materials, reinforced concrete has some disadvantages, which include low tensile strength, high cost of forms needed to contain the fresh concrete, and the requirement of falsework to support forms until the concrete has gained sufficient strength to safely support itself. In addition, concrete needs mixing, casting and effective curing in order to achieve its required strength, and to minimise cracks, which are possible in this type of construction due to shrinkage, creep and the application of live loads.

2.3 Reinforced Concrete Trades

The major trades associated with reinforced concrete construction are falsework/formwork, reinforcing steel, concreting and finishing. Falsework is used to temporarily support formwork and the deposited concrete until it has gained sufficient strength to safely support itself. Formwork, also referred to as shuttering, is used to obtain a shape in concrete. It includes the actual material in contact with concrete and all the necessary associated supporting structures. Falsework and formwork are removed in a process called striking or stripping.

Because concrete material is weak in tension, reinforcing steel bars are added to concrete. The fabrication process can take place off or on-site depending on the quantity and details of reinforcement. Placing and tying steel reinforcement bars is one of the most labour-intensive activities on construction sites and requires high degree of strength, skill and speed.

Concrete placement and surface finish follow placing and tying reinforcement in position. Several placement methods are used, however, pumped and skipped concrete are the two mostly used methods on building construction sites.

2.3.1 Formwork

The type of formwork used, framing system and the geometry involved in the process would have a direct influence on the labour productivity of the trade [34,61,88,99,100].

Formwork types are grouped according to their application as follows [92]:

a) vertical formwork, where the concrete lateral pressure is the governing factor. Examples of this type involve columns and walls; and

b) horizontal formwork, where the weight of concrete and not the lateral pressure is the governing factor. Suspended slabs, decks, and cantilever structures are prime examples of this type.

Formwork is expensive. Table 2.1 illustrates the cost breakdown for the reinforced concrete frame of a typical office building six storeys in height. Figures include cost of materials expressed as a percentage of the total cost [56].

Table 2.1 Cost Breakdown for a Typical Reinforced Concrete Office Building Six Storeys in Height

MEMBER	*COLUMNS*		*BEAMS*		*SLABS*		*WALLS*		*OVERALL*
FORMWORK	*4.5%* (24.4%)	+	*8.5%* (33.0%)	+	*18.5%* (47.7%)	+	*8.0%* (53.1%)	=	*39.5%*
REINFORCEMENT	*12.0%* (60.9%)	+	*14.5%* (56.3%)	+	*3.0%* (7.1%)	+	*3.5%* (23.8%)	=	*33.0%*
CONCRETE	*3.0%* (14.7%)	+	*3.0%* (10.7%)	+	*18.0%* (45.2%)	+	*3.5%* (23.1%)	=	*27.5%*
TOTAL	*100.0%*		*100.0%*		*100.0%*		*100.0%*		*100.0%*

It can be seen from the figures shown in table 2.1 that formwork is the most expensive component. In the United States, cost of formwork ranges from one-third to two-third of the total cost of the reinforced concrete frame [56]. Consequently, formwork should be carefully handled and reused as many times as possible. Designers should aim to maximise the number of times forms can be reused and minimise both erection and striking times. In addition, standardisation of dimensions, rationalisation of design schemes and repetition of element sizes, as much as practical, throughout the project are essential to ensure efficient and cost-effective utilisation of formwork materials.

A wide variety of materials is used for all parts of formwork. The most common material however is timber, also known as "traditional" formwork [14]. Timber has the advantage over all other materials because it can be easily cut, handled and assembled on site. Timber is used as bearers in soffit forms as well as waling in wall forms. Plywood is mainly used for panels. Both traditional and proprietary formwork use plywood, which is by far the most common sheathing and soffit material used. The two main types of plywood in use are Douglas fir and Birch. The thickness of plywood used for formwork is 18 to 19 mm, and the standard sheet size is 1220 x 2440 mm. Larger sheet sizes however are available upon request.

Fibreboard is mainly used as a lining material and is especially useful for forming curved and irregular surfaces. The main type used for formwork is the hardboard. Hardboards are available in thicknesses ranging from 3 to 6 mm. The disadvantage of this type however, lies in its limited reuse potential. Standard hardboards are suitable for one use only [14].

Woodwool sheets are produced in thicknesses ranging from 25 to 100 mm. Due to their advantages of excellent thermal, fire-resisting and acoustic properties, woodwool sheets are most suitable for permanent formwork soffits [14].

Metal forms made of steel and aluminium are used for proprietary formwork [14]. The components of this system are bolted or clipped to each other and to the supporting falsework. Such formwork type is economical when a high degree of repetition is involved in the shuttering process. Proprietary metal forms are available for hire from different suppliers. This system includes steel floor centres for both, slab and wall construction, steel framed panels with plywood or steel sheathing for the use in walls, columns, beams and slabs, column and beam clamps, wall ties, amongst other ironmongery and fittings. Special purpose, custom–made metal forms can be manufactured for a specific contract; cost/benefit ratio however, should be carefully investigated.

The advantage of proprietary metal forms comes from its high reuse potential provided they are properly handled and maintained. Their disadvantages however lie in their lack of adaptability, difficulty in fixing inserts and box-outs, high weight which makes cranage necessary for lifting, erection and stripping, poor insulation property which causes high heat loss during the concrete curing process, and finally, their impermeability causes blow holes in the concrete finish caused by air bubbles trapped against the form face [14].

Plastic formwork can be an economical choice only if high finishing quality is required and a high degree of repetition is involved. Their advantages come from their low weight, stability, potential reuse value, the ability to form complex shapes and produce high quality finish. Their disadvantages are high manufacturing costs, susceptibility to damage, surface scratching and low rigidity [14].

Glass Fibre Reinforced Plastics (GRP) are most suitable for waffle moulds, mushroom headed circular columns, and other complex shapes. In addition to GRP material, foamed plastic (polystyrene) is used as a disposable formwork material. It is mainly used in making pockets, forming voids, holes and other ornamental features. It has the advantage of being easy to remove by poking out [14].

Most formwork systems however are made from a combination of different materials. Traditional timber and plywood formwork use metal clamps, metal ties and steel props as the decking support system. Proprietary formwork can be a combination of steel and plywood which is used for walls, columns and slab soffits. Aluminium ledgers, joists and soldiers with timber inserts are used as wall forms and slab soffits. In fact, a wide variety of combinations can be utilised in formwork.

It is important to mention however that formwork labour productivity would be influenced by the type of material used [61,88]. In order to minimise such an influence, construction sites employing similar materials for formwork should be selected for observation. Due to the previously stated advantages of traditional timber material, and the abundance of construction sites utilising such formwork material, the traditional timber formwork will be selected for observation in this research project.

2.3.2 Reinforcing Steel Bars

Since concrete material is weak in tension, reinforcing steel bars are added in the tension zones of the structural members. The compatibility of concrete and reinforcing steel bars is high. The advantages of each material compensate for the disadvantages of the other, and the two materials bond together to act as a unit in resisting stresses [77].

According to the American Society for Testing and Materials (ASTM), the nominal available sizes of reinforcing steel bars are 10, 15, 20, 25, 30, 35, 45, and 55 mm [68]. On the other hand, the British standard nominal available bar sizes are 6, 8, 10, 12, 16, 20, 25, 32, 40, and 50 mm, where the nominal bar size is the diameter of an equivalent circular area [50].

2.3.3 Fixing Reinforcing Steel Bars

Fixing reinforcing steel involves placing and tying bars in positions. The most common method of tying reinforcing steel is to use soft iron binding wires at selected intersections of bars in slabs, footings, and walls, and at intersections of main bars and stirrups or links in beams and columns.

Reinforcing steel fixing requires a high degree of strength and skill. Firm fixing and holding reinforcing bars in position is essential during concrete placing and under foot traffic in order to maintain the design effective depth for members. Spacers are used to maintain an adequate concrete cover to protect the reinforcement from rusting and expanding due to air and moisture penetration. The most commonly used type is the plastic spacers which are made to fit particular bar sizes. Mortar blocks may be also used as spacers to ensure the provision of adequate cover. For deep slabs, on site cut and bent steel chairs are usually used to support and provide the minimum required cover for the top reinforcement layer.

Depending on the scale of the project and details of reinforcement, steel bars are delivered to construction sites either as straight bars in standard bundles of twelve meters in length and two tons in weight, or cut and bent to sizes and shapes off site. Cutting and bending, and fixing of reinforcement are two distinct activities which may be performed by two different gangs on site. Furthermore, prefabricated reinforcements can also be preassembled into cages which may be lifted and fixed in positions.

2.4 Concreting

Concreting and finishing of members are the final steps after forming and fixing reinforcement in place. Several placing methods of concrete are available, but the most universal two are the skipped and pumped methods. Skipped concrete requires the use of mobile crane, hoist or overhead cable way. Concrete skips, also referred to as buckets, are available in different standard volumes ranging from one-third to two cubic meters. Concrete pumps on the other hand are powerful tools and most suitable for large volume placement of concrete. Over a quarter of the concrete on North American construction sites is placed by pumps [70]. Other methods of concrete placement are also used. They include slip forming, shotcreteing and tremie concrete.

2.4.1 Concrete Workability

The workability of concrete is often defined in terms of the amount of mechanical work or energy required to produce full compaction and consolidation of fresh concrete without segregation [70]. The term workability is mainly used to refer to the compactability, mobility and stability of fresh concrete. Compactability is the ease with which concrete can be consolidated whereas, mobility and stability refer to the ease with which concrete flows into forms and around the reinforcement and its ability to remain coherent, stable and homogeneous during the vibration process. Workability of concrete is measured on sites by the slump test, however, the oldest measure of workability, still widely in use, is the subjective assessment of fresh concrete by an experienced worker. Concrete is described as being of high, medium or low workability [70].

2.4.2 Concrete Compaction and Consolidation

Once the concrete is placed, it is ready for compaction and consolidation. Consolidation of fresh concrete is an important process. Concrete should be compacted to eliminate voids and entrapped air and to be consolidated around the reinforcing steel bars and into the corners of forms. Inadequate compaction and consolidation of concrete could result in reduction of strength, increasing surface permeability, impairing contact between the mix and reinforcement and production of blemishes on struck surfaces [15]. The universal means for concrete consolidation is vibration. Vibrators apply periodic forces with an eccentric rotating mass. Under the shear forces accompanying the vibration, the concrete flows and is compacted away from the vibrator. When the use of immersion vibrators is not possible due to congested reinforcement, narrow spaces, or slip forming, external vibrators can be clamped to formwork. However, forms must be rigid and strong enough to withstand the combined pressure and weight of placed concrete and vibration forces.

The time needed for vibration for adequate consolidation ranges between 10 to 20 seconds. Vibration should stop when cement paste begins to appear around the vibrator. Over-vibration may lead to segregation of concrete especially in high-slump mixes. On the other hand, under-vibration can cause honeycombing since coarse aggregate and mortar will not have enough time to flow to the same extent. It should be noted that vibrators have a limited "sphere of influence". Consequently, to attain proper consolidation of concrete, vibrators should be inserted into concrete at close intervals, normally 18 in. (450 mm) apart to ensure overlapping of spheres of influence. Another important effect of vibrators is forcing entrapped air out of the concrete. The most efficient way to remove the entrapped air is to plunge the vibrator rapidly into the concrete surface and remove it slowly with a "jigging" motion. Rapid penetration forces the concrete upward helping entrapped air to escape, and when the vibrator is withdrawn slowly, the air is forced upward ahead of the vibrator [70].

2.4.3 Concrete Surface Finish

Finishing of concrete can take many forms and patterns. The most used patterns include levelling, screeding, floating, trowelling and texturing. Levelling is the most basic type of concrete floor finish. This process involves striking the excess concrete for proper grade and level. Screeding can be done manually or mechanically. The screed is moved back and forth across the concrete surface in forward motion. Vibration can be utilised in the screeding process. A float is used after screeding to embed large aggregate and to level the surface by removing any remaining bumps and hollows.

When the concrete surface has hardened, all bleed water has disappeared from the surface and has gained enough strength to permit operation, the surface is floated with flat wood or metal blades. This process embeds aggregate particles, removes any imperfections and compacts the surface. It should be noted however that over floating can be damaging and would weaken the surface as floating tends to bring the cement and water to the surface which forms a high water/cement ratio layer of paste [70].

If a smooth, dense and wear-resistant surface is required, the surface may be power-trowelled. More than one trowelling can be done to the surface if required. However, a power-trowelled surface will be prone to slipping or skidding, therefore, a textured surface may be specified for improving skid resistance. The most common method for texturing is scoring the surface with a wire broom.

Decorative aggregates may also be applied over the top of freshly cast concrete followed by floating and trowelling.

Based on the preceding literature, it may be concluded that each type of the previously explained surface finish requires different technique and is characterised by a certain task level difficulty, which would also influence the labour productivity of the trade. However, due to the difficulty in collecting adequate sample size of productivity data points pertaining to the various reviewed finishing types of concrete, a meaningful comparison amongst labour productivities of each type may not be possible. Consequently, the observation in this research project will focus on the most common type of floor finish; the power-trowelled.

2.5 Buildability

The word buildability, appears to have first entered the language in the late nineteen seventies [20]. An early attempt to address buildability can be credited to Sir Harold Emmerson when he suggested a new form of relationship between designers and constructors [71]. The point of concern was the lack of cohesion between designers and constructors and the inability of both parties to see the whole construction process through each other's eyes.

Constructors asserted it was the designers' fault and responsibility that the cost of buildings is high, and that the building designers were not enabling the clients to obtain the best possible return value for their investment. Designers equally blamed the industry for not being able to realise their designs in the best possible economical way.

This conflict has encouraged a major research effort into approaches to identify the root cause of the problem in order to bring design and construction professionals to work more closely together.

2.5.1 Definition of Buildability

In an exploratory report, "Buildability: an assessment", published in 1983 by the Construction Industry Research and Information Association (CIRIA), buildability was tentatively defined, and perhaps it is the most widely accepted definition, as: "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building" [23].

Based on this definition, two implications can be inferred. First, buildability can be categorised in a scale ranging from good to bad, and second, that each building has overall requirements which may conflict with the buildability concept and necessitate the acceptance of less than good buildability.

However, the conclusion of the CIRIA report can be summarised as follows:

a) good buildability leads to major cost benefits for clients, designers and builders; and

b) the achievement of good buildability depends upon both designers and builders being able to see the whole construction process through each other's eyes.

In attempts to enhance the understanding of buildability concepts, many researchers elaborated on the definition in their work. Illingworth, as reported by Moore [71], stated that "the British construction industry would only be able to equal the efficiency of its global competitors by studying, and acting upon the requirements of buildability".

Ferguson [32] defined buildability as "the ability to construct a building efficiently, economically, and to agreed quality levels from its constituent materials, components, and sub-assemblies". Griffith [41] on the other hand, suggested "a compromise between consciously making the design more buildable and accommodating the many factors imparting an influence upon design including quality, aesthetics, time and cost".

Hyde [55] believes that the previous definitions of buildability "lack precision when placed into operation in the design environment". He concluded that, buildability is not an absolute goal or quality as has been identified by many researchers, rather it is related to qualitative aspects of buildings and the level of complexity involved in the process. He went on to suggest "clear direction or modus operandi to be developed for buildability assessment, and that the knowledge should progress from operational principles to designers to achieve the level of buildability desired".

Moore & Tunnicliffe [71] also suggested that there has been an inconsistent approach in defining and applying buildability, and went on to stipulate that buildability is "that design philosophy which recognises and addresses the problems of the assembly process in achieving the construction of the designed product, both safely and without resort to standardisation or project level simplification".

Throughout Europe, the expression "Buildability" is the adopted terminology for the influence of design on the construction process. On the other hand, the term "Constructability" is widely used and favoured in North America. Although both expressions target similar issues, the term constructability covers wider range of disciplines including conceptual planning, design, procurement and construction.

The constructability task force of the Construction Industry Institute (CII) defines constructability as [22]:

"The optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives".

Despite the slight difference in the approach taken to define the concept, both buildability and constructability focus on the utilisation of construction experience at an early stage of the design process where the possibility to reap the constructability benefits is highest.

Based on the aforementioned discussion of the several definitions of buildability suggested by different researchers, we may conclude that buildability is a function of the design process and has a direct impact upon the construction cost, time, labour productivity as well as sequence of operations.

Moreover, we may infer that buildability, in its broad term, involves the influence of all design disciplines such as architectural, structural, electro-mechanical and finishing specifications on building construction projects. Therefore, the "total" buildability of a project would be the sum of the effects of the "partial" buildability factors of the various design disciplines on the construction process, and the inter-relationships of such disciplines as well as their consequences on the operational sequences. In view of this, we may re-define buildability as follows:

a) total factor buildability, which includes the total effect of all design disciplines; and

b) partial or single factor buildability, which involves the effect of a single or selected design disciplines on the construction process

In this research, the influence of partial buildability factors such as architectural, structural and concrete specifications on the labour productivity of the relevant reinforced concrete trade at both levels, macro and micro, will be investigated and quantified. Architectural factors in this study involve grid patterns, geometry of elements, height of stories and the specified concrete surface finish. Structural factors include the type of floor framing system, dimension of elements, rationalisation of design, standardisation and repetition of members, reinforcing steel quantity and diameters, location and congestion of reinforcement, and the specified concrete workability.

As was previously explained however, besides buildability, other factors affect labour productivity. Thus, to unravel the effects of buildability factors and minimise the influence of other factors, it is important to select, for observation and data collection purposes, construction sites which share, as much as possible, common characteristics such as type, construction methods, site management, contract procurement method and geographical location.

2.5.2 Historical Review

Buildability has existed since mankind erected simple shelters utilising available raw materials and primitive hand-made tools. Buildability was the basis of design in the 14th century [25]. However, the concept of buildability in that era was governed by what was considered capable to safely stand against the forces of nature such as, wind, rain and snow, in addition to its own weight. Major early structures were constructed of timber due to the abundance of the raw material on the one hand, and its easiness and flexibility to handle and work with on the other. With practice and over the time, construction skills were developed and the stone material was widely used in the construction of residences.

In that era, design and construction, from conception to completion, was performed and supervised by skilled craftsmen or "Master Builders". This practice continued until the Renaissance, when the architectural profession emerged, and the separation of design and construction activities was initiated [72].

Designers of the Renaissance era placed more emphasis on the aesthetic aspect of projects and alienated themselves from the mechanics of the construction activities. This behaviour is best illustrated by quoting the Italian Architect Alberti, who believed that "an architect is not a carpenter or joiner. The manual worker being no more than an instrument to the architect, who by sure and wonderful skill is able to complete his work" [29].

The development of modern construction techniques, the introduction of new construction materials such as structural steel and reinforced concrete, the scientific progress and the establishment of technical institutes accompanying the industrial revolution era, served to further detach and dissolve the association of design and construction.

Currently, the construction industry is even more fragmented. Professionals within the industry comprise architects, civil, structural, mechanical and electrical engineers, quantity and site surveyors, constructors, and various craftsmen, each having a specific role during both design and construction stages.

2.5.3 Importance of Buildability

Most of the studies conducted on buildability suggest that buildability, if considered in the early stage of the design process, brings about large benefits in terms of costs and time to the construction industry.

Despite the revolutionary advancements made in building materials, training and construction technology, the construction industry has been plagued with a steady increase of unit costs compared to other industries, especially computers and aircraft as shown in Figure 2.1.

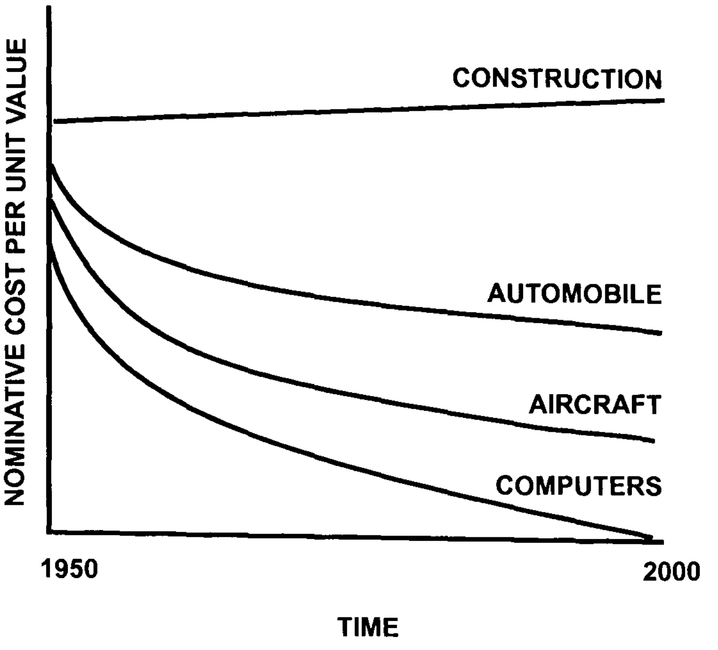


Figure 2.1 Economic Progress over Time in Different Industries (Source: Paulson, B.C. 1995)

As an economic principle, when the cost of an industry increases, it becomes less attractive to potential investors, consequently, its contribution to the national Gross Domestic Product (GDP) decreases. If the construction industry has to be competitive, then construction costs have to be reduced. The ability of buildability to make a difference in the construction project largely depends upon its implementation in the early stage of the design process.

Figure 2.2, explains the level of influence on project cost for the three main stages of a construction project [84]. The control level varies according to the stage of the project.

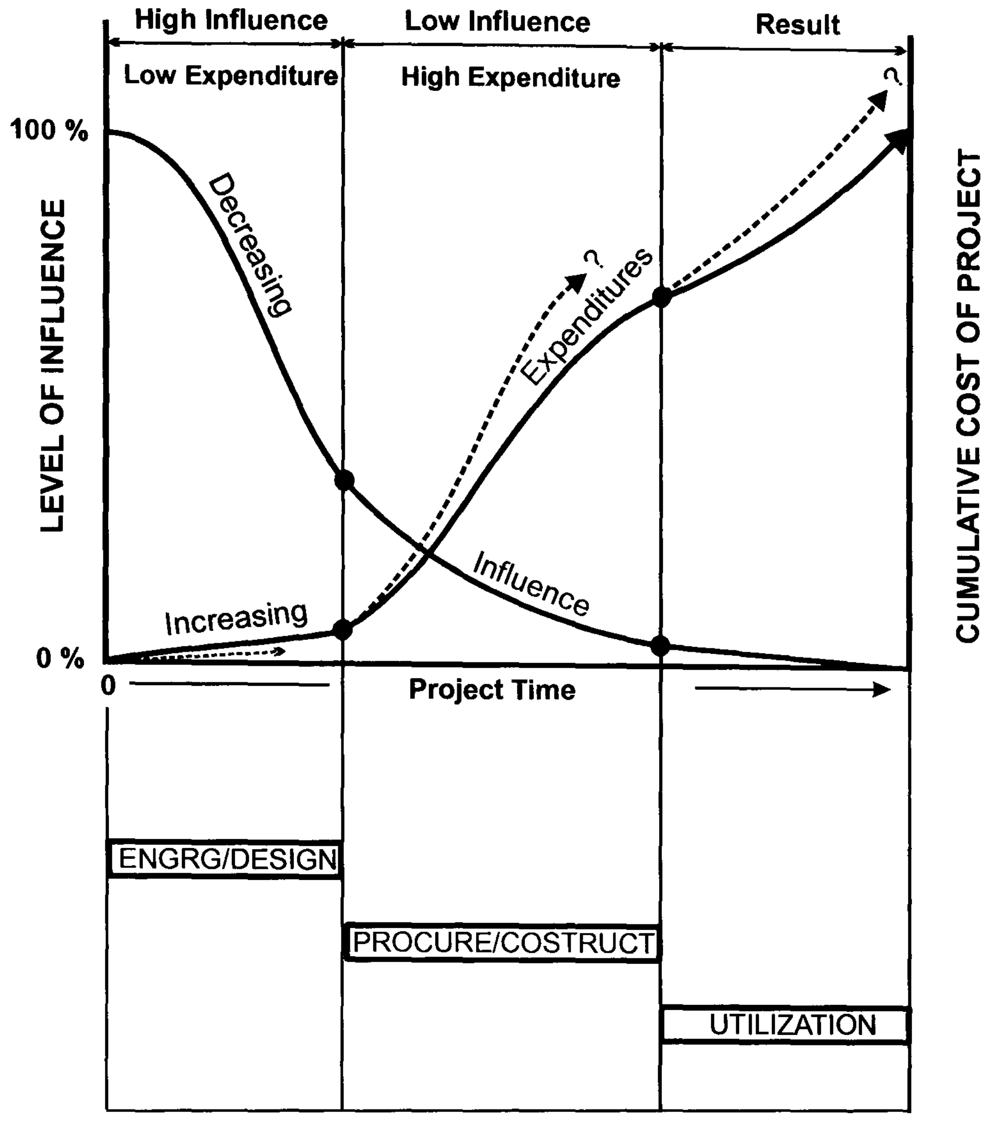


Figure 2.2 Level of Influence on Projects Costs [84]

Decisions made during the design stage not only have the maximum influence on the cumulative cost of the project, but would also dictate the future expenditures and durations, even though it accounts for only about 10% of the project expenditures.

As the project approaches the procurement and construction stage, the level of influence decreases, and the ability to control costs decreases too. At the operational phase of the project, the level of influence on cost is minimum. It should be clear then, that in order to lower the total project cost, attention should be focused on the design stage where the control level is maximum, and the implementation of the buildability principles affords the most influence. Therefore, it is false economy to exert pressure on designers to keep design costs low. More opportunities exist to significantly lower the total project cost by focusing more attention on the design process than on the construction phase.

2.5.4 Factors Influencing Buildability

Adams [1] attributed poor buildability to the current architectural education system. He suggested that the building construction subject has no or little emphasis, and that new graduates choosing the design career, are largely unaware of most construction procedures. Ferguson [32] highlighted poor buildability in a number of areas including site investigation and planning, lack of understanding by designers of the standardised building materials and components, poor communication of project objectives and the addition of unnecessarily complex architectural features.

Adams [1] further advocates the integration of the design and construction functions in order to create coherent, efficient and economical solutions to construction projects. However, designers in the construction industry continue to practise separately from the constructors allowing little or no input of construction experience to be incorporated into the design stage when its influence is highest.

Design simplification is achieved through the implementation of the following three major buildability principles: a) rationalisation; b) standardisation; and c) repetition of elements [25,34]. Complex design and details increase task level difficulty which would result in substantial delays and low productivity of the construction activities. Simplicity however, is not intended to curtail the design process or limit the construction innovation, it should be progressive not reactionary [115].

Design rationalisation is defined as "the minimisation of the number of materials, sizes, components or sub-assemblies" whereas standardisation is "a design philosophy requiring the designed product to be produced from those materials, components and sub-assemblies remaining after design rationalisation has taken place" [73].

Design rationalisation and standardisation provide site efficiency, predictability, regularity and better value for money [24]. Standardised elements promote greater repetition, waste reduction, and minimise on-site cutting and fixing. It is through standardising building elements, such as dimensional grids, foundations, columns, walls, beams and module sizes throughout the project that the constructor can ensure efficient and cost-effective operations, and benefit from previous experience and established solutions.

Legible, clear, coordinated and detailed drawings are essential to express the designer's intentions to the constructor, and facilitate ease of construction by allowing smooth and undisrupted operations on site thus, further enhancing projects' buildability and productivity.

Another important factor having an effect on project buildability is the contract procurement method. Traditional procedures provide no involvement of the constructor during all phases of the design process. Normally, the constructor has no contact with the design team until the contract documents are finalised and released for tendering purposes. Again, little or no construction experience is incorporated into the design. Consequently, any useful views that the constructor might have to simplify the construction process, are usually "too late" to be considered and incorporated at this stage due to the limited available time between the call for tenders and the construction start up.

However, a number of contract forms are useful for buildability purposes. Design and Build (DB), and Design-Build-Operate-and Transfer contracts (DBOT), have the advantages of integrating the design and construction teams, enhancing the communication efficiency and increasing the speed of completion.

Clients can play an important role in implementing buildability concepts during the early stage of the design process. By offering the right incentive schemes to designers, such as partnering or profit sharing [80], designers can be motivated to embark and act upon implementing buildability principles when formulating their design concepts and preparing the technical specifications, all of which would enhance the buildability and site efficiency of projects, and again, provide the client better value for money.

However, most of the previously reviewed research discussed the factors influencing buildability on a global basis overlooking an important aspect to the problem such as the impact of design buildability factors, i.e. design variables, on the micro-elements comprising the building. Furthermore, as was previously suggested, buildability should be sub-divided into partial factors pertaining to the various design disciplines of buildings. The author suggests that, in order to provide a comprehensive and practical solution to the problem, and quantify the total impact of buildability on the construction process, researchers should: a) assess the buildability at the design discipline level; b) examine the inter-relationships amongst those disciplines; and ultimately c) simplify the operational sequences required in the construction process. One of the main objectives of this research is to conduct an investigation to quantify the influence of partial buildability factors, i.e. architectural and structural, on the labour productivity of *in situ* reinforced concrete construction. For simplicity however, the expression buildability, although refers to partial buildability, would be used throughout this study.

2.5.5 Buildability Measurement

One of the barriers, and perhaps the most important, to the implementation of buildability principles, is the difficulty in measuring its benefits to the construction industry.

The first attempt to measure the influence of design on buildability was undertaken by the Building Research Station (BRS) [71]. The operation of cranes on various construction sites was examined, and the report (BRS 1970) concluded that "if the site layout or the type of construction utilised make the crane operation difficult, then the whole construction process would be difficult and uneconomical". However, such an attempt failed to quantify the difficulty level associated with the site layout or type of construction.

Another attempt by the Royal Institute of Chartered Surveyors (RICS), was a comparison between construction operations of the UK and the US, with emphasis on design and contractual procedures. In their report (RICS 1979), they concluded that "design can not be divorced from construction without major time and cost penalties"[71]. Again, the magnitude of such time and cost penalties was not determined.

The Construction Industry Research and Information Association (CIRIA) programme of research, identified a constraint for achieving good buildability by stating that "the achievement of good buildability depends on both designers and builders being able to see the whole construction process through each other's eyes" [23]. Having identified this constraint however, no suggestion on how to assess or measure the achievement of good buildability was indicated.

The evaluation of buildability was also addressed by Gray [38,39]. Gray concluded that due to the complex nature of the construction process, there is no single best way to analyse or quantify the design implication on the construction process, and that the analysis should also consider other variables such as construction time, construction cost and the sequence of operations.

Based on the aforementioned discussion, in none of the mentioned examples, were there any quantified or quoted figures or even a suggestion on how to quantify the buildability impact on construction activities. Furthermore, previous research on buildability did not provide specific guidance on how to improve the constructability of a design. In one of the few text books entirely devoted to buildability, Furguson [32] shows the breadth of factors which must be considered to make a design buildable and provides many examples of buildability problems and suggestions for improvements. Whilst such recommendations allow the classification of buildability issues according to their level of details, they do not link or associate buildability issues to design decisions.

Moreover, much of the background emphasises attention to buildability and constructability during construction planning and operations, with relatively little attention to construction input to the design phase. Notwithstanding that general buildability recommendations and guidelines are available for designers, knowledge bases that support specific and timely buildability input to design decisions do not exist [34]. Consequently, general guidelines and suggestions for buildability improvement can be regarded as exhortations of good practice and common sense, often obtained using "Delphic Research Methods"[20].

2.5.6 The Buildable Design Appraisal System (BDAS)

In an effort to measure the buildability of construction projects, the Buildable Design Appraisal System (BDAS), was established in 1993 by the Construction Industry Development Board (CIDB) of

Singapore [21]. The objective of the BDAS is to assess the influence of design on site efficiency and construction labour productivity.

Buildable design leads to higher labour productivity and lower construction cost [17,25,115]. Consequently, there is a direct proportional relationship between buildability and labour productivity. The BDAS presents a systematic numerical method to evaluate and appraise the effects of design on construction productivity by means of calculating the "Buildable Score" of the design, taking into consideration the level of simplicity, standardization, and the extent of the single integrated elements, i.e. combining related components into a single element which may be prefabricated in the factory and installed on site, e.g. pre-cast concrete external or curtain walls. A set of values or indices are awarded for each type of architectural and structural systems based on the level of difficulty of the construction operation. The structural system, wall systems and other design considerations are measured separately and added to achieve the total buildable score. Designs with high buildable scores suggest more efficient use of labour and therefore higher labour productivity.

It is worth noting however that the BDAS was developed mainly for the general "macro-level" appraisal of the buildability of projects. It includes general appraisal for *in situ* and pre-cast reinforced concrete, as well as structural steel building frames. Major building elements include structural and wall systems, architectural components such as external and internal walls, doors and windows, in addition to other labour-intensive elements. However, other design disciplines such as mechanical and electrical services, as well as finishes are not considered.

A major shortcoming of this appraisal system stems from the lack of depth in which buildability was assessed. Buildable scores were awarded based on the overall structural type and construction method. Such an approach is too general in nature. The influence of buildability factors need to be investigated in far greater depth to establish and accurately quantify their impacts on labour productivity.

Although the BDAS is the only available formal design appraisal tool to date, the scientific reliability of the methodology employed in developing the system's buildable scores is questioned. Buildable scores were obtained from inputs provided by government agencies, private consultants and product manufacturers based on previous personal and group experience [25]. Once again, such an approach can be regarded as good practice and common sense, where the scientific method requires facts to be established through rigorous research, measurement and analysis.

2.6 Productivity

The origin of the word productivity can be traced back to 1766 when it was first mentioned in an article by Quesnay [102]. More than a century later, in 1883, Littre defined productivity as the "faculty to produce", that is, the desire to produce. In the early twentieth century, a more precise definition, the relationship between output and the means employed to produce that output was developed. In 1950, the Organization for European Economic Cooperation (OEEC) introduced a more formal definition of productivity [102]: "productivity is the quotient obtained by dividing output by one of the factors of production. In this way it is possible to speak of the productivity of capital, investment or raw materials according to whether output is being considered in relation to capital, investment or raw materials, etc".

2.6.1 Definitions of Productivity

In the most general term, productivity is an economic measure defined as the ratio of output to input. Depending upon the objectives of measurement and the availability of data, numerous definitions and mathematical expressions are encountered.

The US Department of Commerce defines productivity as Dollars of output per person-hour of labour input [2].

$$\textbf{\textit{Productivity}} = \frac{\textbf{\textit{Dollars of output}}}{\textbf{\textit{Person} - \textit{hour of Labour input}}} \qquad \ldots 2.1$$

Prokopenko, as reported by Langford *et al* [66], regards productivity as "an effective and efficient utilisation of all recourses; labour, plant and materials".

Handa & Adballa [43] defined productivity as "the ratio of outputs of goods and/or services to inputs of basic resources, e.g. labour, capital, technology, materials and energy". It can be expressed as follows:

$$\textit{Productivity} = \frac{\textit{Outputs (goods \& services)}}{\textit{Input (labour, capital, technology, materials \& energy)}} \qquad ...2.2$$

Arditi & Mochtar [12] referred to productivity as "the ratio between total outputs expressed in Dollars and total inputs expressed in Dollars as well", that is:

$$\textit{Productivity} = \frac{\textit{Total outputs \$}}{\textit{Total inputs \$}} \qquad ...2.3$$

As reported by Allmon *et al* [7], the American Association of Cost Engineers, defines productivity as a "relative measure of labour efficiency, either good or bad, when compared to an established base or norm".

Horner & Duff [51] expressed productivity as "how much is produced per unit input" whereas, Peles [86] interpreted productivity as "the performance accomplished by operatives". Finke [33] defined productivity as "the quantity of work produced per man-hour, equipment hour, or crew hour".

Thus, the general consensus to define productivity is the ratio of output to input.

Frequently, efficiency is regarded as synonymous with productivity and expressed as follows [26]:

$$\textit{Effeciency} = \frac{\textit{Output}}{\textit{Input}} \qquad ...2.4$$

It is important to note however that the term productivity is often confused with other terms such as production and speed. Many associate productivity with production or speed and presume that, as the production or speed increases, productivity increases too, and this is not necessarily true.

Productivity is concerned with the efficient utilisation of resources, i.e. inputs, in producing goods and/or services, i.e. outputs, whereas, production is concerned with the activity of producing goods and/or services [26]. In other words, production is the measurement of the amount or quantity produced regardless of the input utilised in the process. As a result, production can be high, but the productivity of the operation might not necessarily be high as well. On the other hand, speed refers to the output produced in unit time without considering the resources involved, i.e. labour, capital, technology, materials, energy, etc. Again, the speed of the process could be high, but not necessarily the productivity.

2.6.2 Construction Productivity

Construction productivity has become such a "Buzz" word and one of the most frequently researched topics due to its importance to the viability of the industry. It is regarded as a true reflection of the efficiency and economic success of the operations [115].

Productivity is defined as the ratio of output to input [2,12,43]. Consequently, construction productivity can be regarded as a measure of outputs which are obtained by a combination of inputs. In view of this, two measures of construction productivity emerge:

Total Factor Productivity (TFP) where all outputs and inputs are considered; and Partial Factor Productivity (PFP), often referred to as Single Factor Productivity, where outputs and single or selected inputs are considered.

A. Total Factor Productivity (TFP)

Total factor productivity is defined as the ratio of outputs to the summation of all inputs, and is expressed in the form of [103]:

$$TFP = \frac{\textbf{\textit{Total output}}}{\sum \textbf{\textit{of all input resources}}} \qquad ...2.5$$

All input resources may include, but are not limited to, labour, material, energy, capital and plant. Total productivity is a comprehensive measure which accounts for all outputs and inputs whether tangible or intangible [86]. To get a meaningful total factor productivity index, outputs and inputs should bear a common base measure unit. As suggested by Thomas *et al* [109], a monetary value base unit would be appropriate to use and the equation would be expressed as:

$$TFP = \frac{\textit{Pound value of output}}{\textit{Pound value of input}} \qquad \text{...2.6}$$

The disadvantages of the TFP measure are twofold. On the one hand, it is difficult to accurately determine and measure all the input recourses utilised to achieve the output, and on the other, it is often impractical, especially for researchers, to monitor or assess the effects of selected individual factors on the output.

B. Partial Factor Productivity (PFP)

Partial factor productivity establishes a relationship between outputs and a single or selected set of inputs [89]. The definition is best exemplified by the term labour productivity, where only the input of labours is considered. Other single or partial factor productivity measures include capital productivity, plant and equipment productivity. Mathematically, PFP can be represented as follows:

$$\textit{Labour productivity} = \frac{\textit{Output quantity}}{\textit{Labour man} - \textit{hours}} \qquad \text{...2.7}$$

$$\textit{Capital productivity} = \frac{\textit{Profit}}{\textit{Invested capital}} \qquad \text{... 2.8}$$

$$\textit{Equipment or Plant productivity} = \frac{\textit{Output quantity}}{\textit{Equipment or Plant hours}} \qquad \text{...2.9}$$

The advantages of the partial factor productivity (PFP) are many. By focusing on a selected factor, the measurement process becomes easier and more controllable. As a result, reliable and accurate data can be obtained. The complex nature of the construction process and the interaction of its activities, make the partial factor productivity measure the popular option since effective control systems monitor each input separately.

Based on the preceding discussion, in investigating the influence of buildability factors on the labour productivity of *in situ* reinforced concrete trades, construction labour productivity is most appropriately quantified and expressed as a "Single Factor Productivity" as the ratio of output, i.e. square meters, kilograms and cubic meters for formwork, reinforcing steel and volume of concrete placed respectively, to the single input of labours, expressed in terms of man-hours as shown in equation 2.7.

2.6.3 Importance of Construction Productivity

In 1997, the US construction industry accounted for 10% of Gross Domestic Product (GDP) and employed over 10 Millions, making the industry the largest in the country [7]. The significance of this influence, clearly justifies the concern over its productivity.

The construction industry in Canada contributed 15% of the GDP in 1989, and provided direct employment to over 780,000 Canadians. This figure reaches 1.5 Million when we consider those engaged in the manufacture, sale, transportation of materials, machinery and equipment utilised by the construction process. It purchases materials worth more than $43 Billions and pays out $31 Billions in wage bills. A 10% increase in construction labour productivity, will save the Canadian economy $3 Billions annually [89].

Horner *et al* [54] indicated that a 10% increase in construction labour productivity would yield annual savings of about £1 Billion to the British Economy. A similar conclusion was echoed by Stoekel & Quirke as reported by Naoum and Hackman [75].

2.6.4 Factors Influencing Construction Productivity

The productivity of the construction industry has been on the decline for over a decade. Despite all the technological advancements in the industry, construction costs have risen at a rate almost 50% higher than the inflation rate, project durations have substantially increased, and many projects have overrun their budgets[12,112]. Why?

In order to investigate this problem, one has to examine the factors which influence and have a direct impact on productivity. Construction projects are unique and diverse. Factors affecting productivity on one project may not necessarily have an influence on another. No two projects are alike; each has its singular aspects. Therefore, benefits derived from the "Learning-Curve" technique may be of little value.

Numerous research and publications have identified major project-related factors which have an influence on construction productivity [4,17,25,34,50,51,74,79,103,114,115]. Horner *et al* [53], in a questionnaire survey to a wide section of British constructors, have identified the 13 significant factors shown in table 2.2.

Table 2.2 Perceived Importance of Factors Influencing Productivity

Factor	**Rank**
Skill of labour force	1
Buildability	2
Quality of supervision	3
Method of working	4
Incentive scheme	5
Site layout	6
Complexity of construction information	7
Gang size and composition	8
Length of working day	9
Availability of power tools	10
Absenteeism	11
Total number of operatives on site	12
Proportion of work subcontracted	13

Kane & Herbsman [48] divided the influencing factors into two main groups:

a) technological factors; and

b) administrative factors

The technological factors pertain mainly to the design of the project, whereas, the administrative factors are related to the construction management. To briefly illustrate the differences between each groups, let us look at the buildability of the project. The complexity of the construction process can be attributed to the design of the project, consequently, it is classified as a technological factor. On the other hand, the selected formwork system by the site management, for instance, is classified as an administrative factor. Talhouni [103] classified four categories responsible for influencing productivity on construction sites; Management related, site related, design related and weather related.

Management related factors include inadequate supervision, improper selection of construction methods, sequencing problems and the unavailability of suitable equipment. Site related factors are caused by restricted access, stringent control procedures and congestion. Design related factors, are the direct result of buildability or the lack of it. It includes uncoordinated and incomplete drawings, complex designs of unusual shapes and heights, stringent inspection procedure and out-dated technical specifications. On the other hand, weather related factors are attributed to cold or hot temperatures, high humidity, high wind, rain and snow.

Another important area which was the subject of many researchers [13,47,63,75,114] is the human factors. This includes labour management relations, wage incentives, physical fatigue, union practices, but above all, the motivation of the work force.

It is interesting to note the consistency amongst most researchers in identifying the most significant construction productivity influencing factors.

2.6.5 Construction Productivity Measurement

Three major techniques are available for measuring and monitoring construction productivity:

a) visual recording technique;

b) physical recoding technique; and

c) questionnaires and interviews

Visual recording technique is used to continuously monitor the performance of operatives on sites. Fondhal [35] who has extensively used this technique can be regarded as a pioneer in the use of the visual recording method for productivity monitoring purposes.

Such a technique involves the use of time-lapse photography [83]. It involves a focused camera equipped with an 8 mm film on a selected work area and a picture is taken at regular time intervals ranging from 2 to 8 seconds. This method offers some advantages over others. It provides accurate, permanent and irrefutable records, which can be used for training purposes, construction claims and contract disputes, investigating crew performance and evaluating the efficiency of construction methods. However, some disadvantages accompany this technique such as creating unrest amongst the workforce being continuously observed, having a limited coverage area and the need for several cameras on large sites rendering this technique uneconomical.

Another visual recording technique is the use of video tape recording system. It basically performs the same function, but captures all or most concurrent activities allowing for fewer observers on site. However, it is regarded as an expensive method.

Physical recording technique requires trained observers to be physically present on site for the purpose of monitoring and recording work performed by operatives. The basic methods employed in this technique are; activity sampling, daily visits and continuous observation.

Activity sampling technique, also referred to as work sampling, is an intermittent observation technique that involves observing a small percentage of project activities that is large enough to have statistical significance [83]. Usually, an observer would walk through the site and records workers' activities. In essence, the activity sampling technique is used to provide a tool for determining how the operatives spend their time on site. It is often assumed that work accomplished or output is correlated with the amount of time spent on direct work.

Activity sampling was extensively used and examined by many researchers and significant findings were presented in numerous technical articles [85,93,105,107,108]. The main advantage of the activity sampling technique is that several trades can be simultaneously monitored by an observer on site.

The major disadvantage associated with this technique however, lies in its fundamental presumption that outputs are directly related to the amount of time spent on direct work. After a comprehensive analysis of the data obtained by activity sampling during the construction of several power plants in the US, Thomas [107] found no correlation between outputs and the amount of time spent on direct work, and concluded that direct work cannot be used to predict productivity since the work sampling technique does not distinguish between busy and effective work. It merely shows how busy the operatives are. The same explanation was given by Peer [85].

The daily visit technique, as the title indicates, is another intermittent observation technique, which requires the observer to visit the site on a daily basis for data collection [74,79]. However, if input measurements are to be recorded by site supervisors or operatives, prior arrangement should be made between the observer and the site personnel to ensure, as much as possible, cooperation, consistency and accuracy of the data provided. The visit takes place towards the conclusion of the work day, usually during the last half hour. The observer collects the recorded input productivity data, and questions the site personnel about the work done, progress and any delays or problems that took place during the workday. Collected data is then cross-checked by a different gang member for verification and accuracy. Finally, completed site work or progress is visually inspected by the observer, and if applicable, marked on drawings. This method has several advantages. Provided that construction sites are in close proximity to one another, the observer can monitor several sites during the same day. In addition, this technique helps to avoid the unrest accompanied by workers being monitored and clock-watched and assists in maintaining good relationship between the observer and site operatives.

However, data collected by this technique depends entirely on the precision and accuracy of the information provided by the site personnel.

The continuous observation technique can be subdivided into direct observation method and work study method.

A. Direct Observation Method

This method involves a trained observer physically monitoring the site for the full span of the working day [77,79]. The observer focuses his attention on a group of operatives and notes the time spent on direct and contributory work. Time that is not spent at work such as breaks, attending to personal needs, late starts and early quits is also recorded. This method provides accurate data and is very useful in determining the distribution of time inputs used to achieve certain outputs.

Major drawbacks of this technique however include discontent and suspicion amongst the operatives being continuously observed, which may lead sometimes to false or inflated productivity, also referred to as the "Hawthorne effect" [26]. In addition, on large sites, more than one observer would be required to effectively monitor the activities rendering this technique uneconomical.

B. Work Study

This method resembles the direct observation technique, but differs in the period of observation conducted by the observer on site. In this method, site observation corresponds to the work cycle of the operation monitored [75]. Therefore, the work study method is suitable for operations with definable cyclic periods.

According to the British standard glossary of terms, BS 3138, Work Study is defined as: "a management service based on those techniques, particularly method study and work measurement, which are used in the examination of human work in all contexts, and which lead to the systematic investigation of all the resources and factors which affect the efficiency and economy of the situation being reviewed, in order to effect improvement" [16].

Based on the preceding definition, work study can be broken down into two main branches, namely, method study and work measurement as shown in figure 2.3.

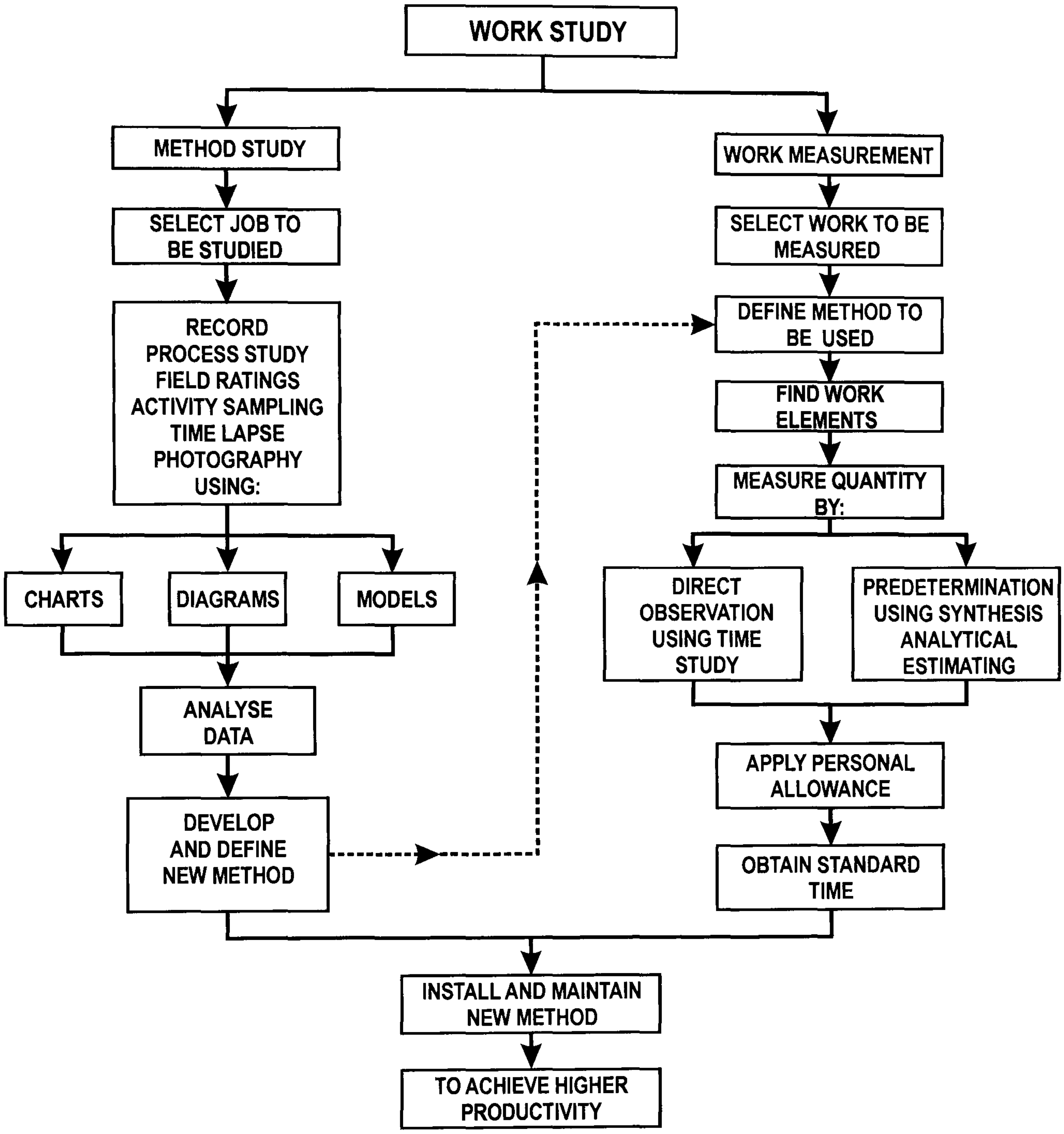


Figure 2.3 Interaction of Method Study and Work Measurement [26]

Method study evaluates the efficiency of the employed methods and work procedures in order to provide systems of analysis geared toward the development of optimal procedures and working conditions [50].

Work measurement, also referred to as time study, is concerned with the measurement of time required to perform different activities within work cycles to provide standard output performance rates. Such rates are used for estimation purposes, setting bonus targets and incentives, and monitoring performance indices, where actual performance is assessed against the standard expected.

The work study method has its origin in the manufacturing industry [26], an industry with a well defined environment, a controlled production process and a known input and output. The construction industry on the other hand, is characterised by its non-repetitious nature, uncontrolled environment and is influenced by many internal and external factors which affect the operatives causing high variations in performance rates.

A comprehensive illustration of the non-steady state of the construction process is presented by Drewin's open conversion system [26] shown in figure 2.4. Furthermore, work study does not measure the actual outputs, consequently, a productivity index, expressed as the ratio of output to input is basically unavailable [103].

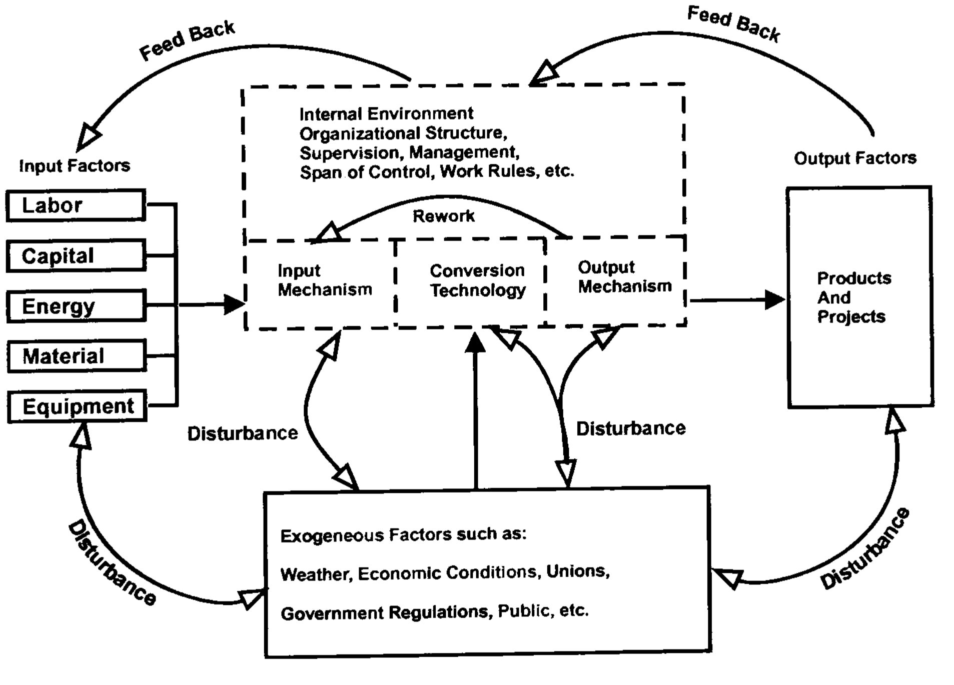


Figure 2.4-a Open Conversion System

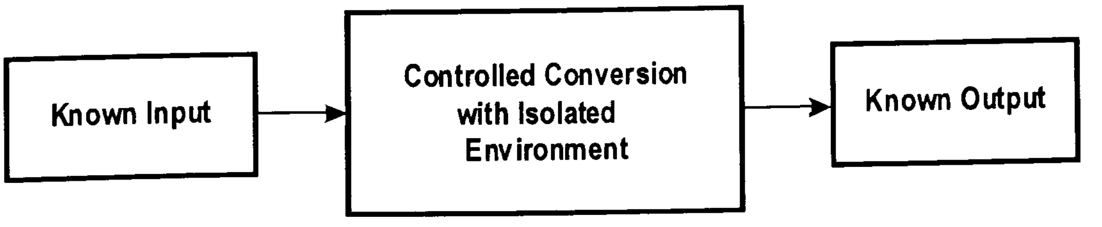


Figure 2.4-b Closed Conversion System

C. Questionnaires and interviews

Questionnaires and interviews techniques involve information gathering through a self-administered questionnaire and interviews amongst construction workers and supervisors with the objective of investigating the factors which adversely affect operatives' performance [82].

Two types of questionnaire surveys have been widely used by observers; the Craftsmen's Questionnaire Survey, and the Foreman Delay Survey.

The Craftsmen's Questionnaire survey is an intermittent observation technique used for measuring management performance and identify problems affecting craftsmen's productivity and motivation [19].

In this method, which is carried out on a regular basis, the craftsmen are asked to provide an estimate of the loss of time on sites, rank the severity of the problems and suggest solutions to these problems. Consequently, managers would be able to recognise problems caused by delays and their possible administrative contributions to these problems.

This technique creates job satisfaction and motivation amongst the craftsmen as it conveys the feeling of contribution to the progress of the job rather than being just an instrument for its completion.

The disadvantages of this technique however are many. Information collected is usually based on the recollections of operatives and on estimates rather than on accurate and specific current information [79]. Another disadvantage stems from the fact that workers are not in a position to objectively identify the causes of some delays as they are not in liaison with the management, which renders the process subjective and prone to inaccuracy. Work may also be disrupted when workers are called upon to complete the forms in privacy for anonymity purposes.

For the reason that the process becomes complicated and tedious when each operative has to complete a form, amongst all other previously stated disadvantages, Chang and Borcherding [19] proposed a new approach, which in essence, resembles the activity sampling technique. In this approach craftsmen are randomly selected and asked to complete the form only on their most recent activities. This leads to improved accuracy and minimises work disruption as workers are approached by the observer at their working area to complete the form "on the spot".

First introduced by Tucker *et al* [113], the Foreman Delay Survey is another intermittent observation method for measuring performance and productivity improvement. The basic premise of the Foreman Delay Survey technique is that foremen, being closest to the work, can identify and estimate time losses at the end of each working day with reasonable accuracy. In this technique, foremen are asked to complete a daily delay report in the form of a check list. The information obtained is analysed, and a summary of lost time is reviewed with all levels of site management including the foremen who contributed the data. With concrete evidence of the cost of delays, and the influence of administrative items, which are beyond the foreman's control, but have a dominant effect on his crew's performance, decisions regarding implementation of solutions is facilitated. Again, this technique creates job satisfaction and motivational atmosphere amongst foremen and their crews as they appreciate the fact that their judgments are valued by the site management.

As with the Craftsmen's Questionnaire Technique however, Foreman Delay Surveys do not provide information on the efficiency of work methods employed, the competence of the work force or the achieved outputs. It does however, provide an economical method of obtaining input times for activities.

Based on the aforementioned discussion of the various observation techniques for the measurement of construction productivity, the selected data collection method largely depends upon the objectives of the research project, types and the sample size of data required. If for instance, observing a single construction site would satisfy the data collection requirements of the investigation, then the continuous observation method would probably be the most effective technique. If, on the other hand, the observation of several sites is needed to acquire the required data, then the intermittent observation method may be the most efficient technique to employ. It is important to note however, that a combination of the previously discussed observation techniques may be employed in a single research project to effectively and efficiently satisfy the requirements for the data collection phase and accomplish the research objectives. In view of this, and since several sites would be observed simultaneously during the data collection phase of this study, the intermittent observation technique will be selected to form the basis for productivity monitoring and measurement.

2.6.6 Output Measurement

Several methods and techniques are available for output measurement. The most used ones however are summarised as follows [103]:

1. physical unit of measurement;
2. percent complete;
3. earned value; and
4. incremental milestone

Physical unit of measurement is the simplest and most common approach to measuring output. It involves quantifying the output based on the actual unit of measurement of the observed activity, e.g. square metres of formwork erected, kilograms of reinforcement fixed, and cubic metres of concrete placed. However, using such a method requires output to be well defined and all associated contributory or subtasks of the activity to be completed. The advantage of this method stems from its accuracy and objectivity, and the fact that claimed output can be readily verified.

Percent complete method is a subjective approach used to estimate the percentage of work completed. This method is usually used for relatively minor tasks where reasonably accurate estimates can be made. The overall accuracy of this method however is questionable since it entirely depends upon the ability of the individual to judge accurately the amount of work completed.

Earned value is another method used to measure output especially when the activity spans for several days. Again, this method is prone to subjectivity since a certain percentage is credited to reflect the amount of work done. It also depends on the existence and reliability of standard productivities or "norms" which are central to the use of the technique. However, it can be regarded as a compromise between the percent complete method and the physical unit of measurement method since it involves greater details and objectivity than simply estimating the percent of work completed, and is less elaborate than measuring the actual output.

The incremental milestone technique is used when an activity comprises sequential work items separated by extended periods of time. This method is best suited where the activity is characterised by a few items and each subtask is difficult to measure.

Based on the previous discussion, throughout this research project, outputs will be quantified using the physical unit of measurement due to its objectivity and accuracy.

2.6.7 The Concept of the Characteristic Items

In its most basic form, the characteristic item is the largest quantity of an item contained in a work package composed of several items.

In an analysis of quantities of similar types of work, Horner and Zakieh [52] found an almost perfect linear relationship between percentage cumulative quantity and percentage cumulative value in two different categories of projects, reinforced concrete bridges and steel framed supermarkets. The linear relationship was apparent for formwork, reinforcing steel and concreting in both project categories.

The linearity of the relationship indicated that a similar relationship exists between quantity and value, and that any marginal increase in quantity would cause a similar marginal increase in value, especially for large quantity items. It was concluded that the influence of large quantity items would overshadow the effect of any differences in rates of small quantities, and that the relationship is dominated by the rate of the largest quantity. Consequently, the unit rate associated with the largest quantity can be applied to all items within the work package. This item, having the largest quantity within any work package, is referred to as the "characteristic item".

The concept of the characteristic item is extremely useful especially for estimation purposes, cost control, and cost modelling. It is equally important in productivity research and studies. An activity such as reinforcing steel fixing is associated with difficulties in productivity measurement due to the variety of reinforcing steel bar diameters, consequently, the application of the characteristic productivity concept would greatly simplify the measurement procedure [65]. The application of the characteristic productivity concept to reinforcing steel trade involves identifying the reinforcing bar diameter which accounts for the majority of the tonnage, "the characteristic diameter", and basing the productivity measurement on the assumption that the productivity of all other bar diameters is represented by the productivity of the characteristic diameter. This approach yields negligible error as the large quantity of the characteristic diameter would swamp the small quantities of all other diameters [51]. This technique is also applicable to a wide variety of trades for productivity measurement purposes.

The Concept of characteristic productivity will be used throughout this research project for labour productivity measurement of reinforcing steel trade.

2.6.8 Input Measurement

Besides choosing the most suitable method for productivity monitoring and measurement, researchers should carefully select the appropriate measurement of inputs.

Depending upon the research objectives, inputs may be measured in three different ways [48,103]:

a) total time;

b) available time; and

c) productive time

Total time is defined as the total paid time and is mainly used for estimation purposes.

Available time is the total time minus "unavoidable" delays. Unavoidable delays include paid breaks and inclement weather. Available time is used to measure management performance.

Productive time is the available time minus "avoidable" delays. Avoidable delays are the results of inefficient site management practices, e.g. poor site coordination, sequencing problems, lack of materials and instruction delays. Productive time is used to measure the skills and capabilities of the labour force and the effect of design variables, i.e. buildability of projects.

Since one of the main objectives of this study is to investigate the influence of buildability factors on labour productivity of *in situ* reinforced concrete trades, throughout this research project, productive time would be used in the measurement of labour inputs, where all delays, whether unavoidable or avoidable, would be discounted, and only time spent in achieving outputs would be used in quantifying labour productivity indices for trades under investigation. Outputs, on the other hand, would be quantified from drawings, bill of quantities and concreting records using the physical unit of measurement as was previously indicated.

It is important however, upon determining the input measurement, to distinguish between two types of short delays encountered on construction sites.

The first type, which is referred to as "Interruption", is the result of circumstances which are severe enough to cause temporary halt to the progress of the activities as well as the production process [65,103].

The second type encountered is called "Disruption". Disruption is caused by events imposed on the labour force or the work area at the crew level, causing slow progress of work, but not a complete stoppage, for a minimum duration of one-half the work shift, i.e. typically four hours or more [103].

Previous research conducted by the Construction Management Research Unit (CMRU) at the University of Dundee [50,51,65,74,79,95,103,115], showed that interruptions lasting less than fifteen minutes had no or little effect on site productivity. Such short breaks may be needed for the work force to attend to personal needs and avoid fatigue in order to perform effectively for the complete shift. Therefore, delays lasting for less than fifteen minutes can be discarded in the intermittent measurement of macro-level inputs for construction productivity monitoring purposes.

2.7 The Learning Curve Concept

A learning curve is a graphical representation of the relationship between unit production time and the number of units produced [82]. The learning curve concept is based upon the premise that individuals, gangs or organisations become more efficient at doing a task when they perform the same task repeatedly. The learning curve concept was first recognised in the aircraft industry when the direct-labour hours required for assembly work were considerably reduced as the task was repeated. In 1936, T.P. Wright disclosed the results of an empirical test showing that as the average number of units produced doubled, the time needed to produce the units decreased at a specific rate [25].

Many field operations of a repetitive nature may also exhibit the learning phenomenon, in which the time required to complete a cycle decreases as the number of cycles increases. Learning curve data can also be presented in units such as man-hours per cycle, Dollars per cycles and so on, depending upon how the output and input are associated with the observed operation. The learning curve is generated when the time or cost required to complete a cycle of an activity is plotted as a function of the cycle number. A typical learning curve is shown in figure 2.5 below.

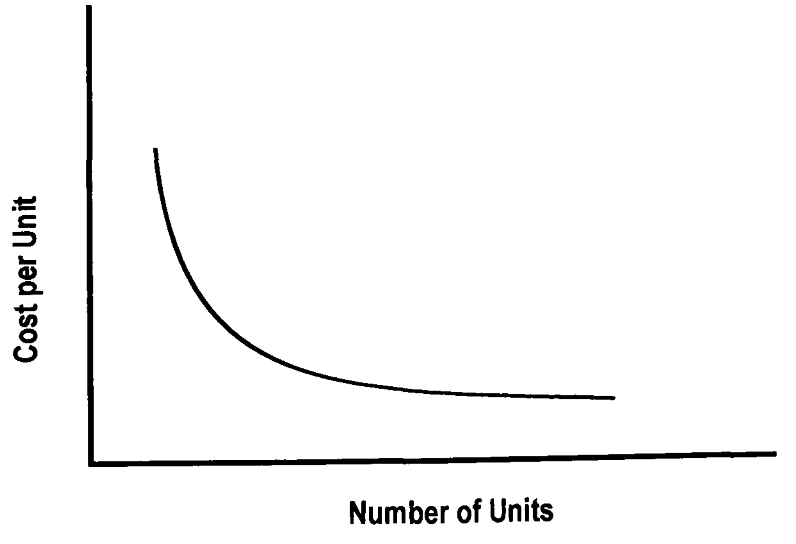


Figure 2.5 Typical Learning Curve [25]

2.7.1 Learning Curve Theory

Despite the existence of different terminologies for the learning curve, at the most basic level, they all describe one phenomenon: as the number of produced units increases, the resources required per unit of production, i.e. man-hours or cost, decrease. The learning curve theory is based upon a basic principle of human nature: the ability to learn from past experience. The learning process stems from individuals or gangs repeating the same task and gaining skill or efficiency from their own experience or practice. This acquired experience is attributable to: a) increased knowledge about the task being performed; b) greater familiarity with the task; c) improved work organisation; d) better coordination; and e) more effective use of tools and methods [110]. On the other hand, organisational learning results from practice and changes in strategy, procedures and administration.

The learning curve theory states that whenever the production quantity of a product doubles, the unit or cumulative average cost, i.e. man-hours or cost, declines by a certain percentage of the previous unit or cumulative average rate. This percentage is referred to as the learning rate, which identifies the learning achieved in the process. Moreover, it establishes the slope of the learning curve. The lower the learning rate, the greater the learning achieved. A learning rate of 100% indicates that no learning takes place [110].

The expected range of learning rate for most construction activities falls between 70% and 90% [83]. What this means in simple terms is that if a certain hypothetical activity follows the 70% learning curve, and if the cost to construct the first unit or cycle is 200 man-hours, then it would take 200 x 70% or 140 man-hours/unit on average to construct the next two units and would take 140 x 70% or 98 man-hours/unit on average to construct the next four units, etc. As the number of units or cycles increases, the production rate stabilises as operatives become completely familiar with the produced task or activity. However, as we have previously indicated, the learning rate remains constant during the whole activity cycles. Arithmetic plots of typical learning curves are shown in figure 2.6.

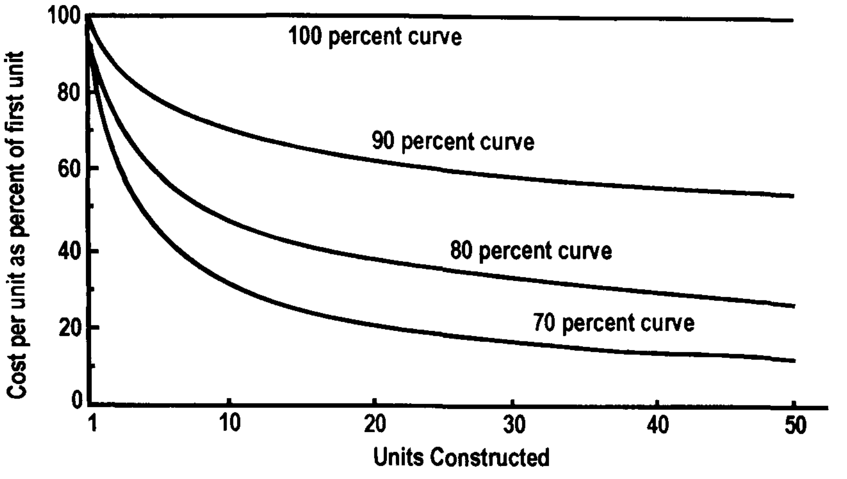


Figure 2.6 Arithmetic Plots of Typical Learning Curves [83]

However, it is worth mentioning that the learning curve theory can only be applied where the activity is repetitious, continuous and identical, i.e. the work is a repeat of the same operation, and there are limited interruptions and delays. In addition, although intuitive, the theory assumes that the same individuals, gangs or organisations are involved in the repeated tasks.

2.7.2 Learning Curve Models

To obtain most benefits from the learning development, researchers focused on developing mathematical models, or learning curves, which describe the time per cycle as a function of the cycle number. The objective of such mathematical models is to provide, predict or measure improvements in productivity through repetitive work.

Five basic mathematical learning curve models have been reviewed in the literature [110]. The various models are:

a) the straight line model;

b) the Stanford "B" model;

c) the cubic power model;

d) the piecewise model; and

e) the exponential model

Of the five models, the straight line and the Stanford "B" models, which were developed in 1936 and 1940 respectively, are based on the assumption that the learning rate is constant. The Stanford "B" model however takes into consideration previous experience adjustments.

The cubic power model was developed in 1970 to account for workers' experience in the first few cycles and also a levelling-off in improvement as the project approaches completion or as production reaches a steady state. Unlike the straight line and the Stanford "B" models, the cubic model assumes that the rate of learning may change over time and is not a constant variable. Cubic learning curve models have been shown to provide the best statistical fit for empirical data from the electronics industry [110].

The piecewise learning curve model is a linearised approximation of the cubic model with three distinct phases, each with a constant rate of learning. When plotted on a log-log scale, this model appears as three- straight line segments. The first phase is called the operation learning phase, the second phase, is referred to as the routine acquired period, and the third phase is designated as the standard production. The standard production phase occurs when the production rate levels-off or ceases to improve, i.e. steady state.

The exponential learning curve model, which was developed by the Norwegian Building Research Institute in 1960, is based upon the assumption that part of the time per cycle is fixed and part is subject to improvement through repetition. This model states that the part subject to improvement will be reduced by one-half after a constant number of cycles, also referred to as the "Halving Factor", and the time per cycle will gradually approach an ultimate or lowest value.

The fundamental problems with the discussed learning curve models are summarised as follows [110]:

1. determining the best predictive model;
2. understanding the variables influencing the rate of learning;

3. estimating the learning curve model parameters, especially the ultimate or steady state time per cycle; and
4. quantifying the impact of delays on performance

Previous studies [27,30,110] were conducted to evaluate the predictive capabilities of the various learning models. However, conflicting and inconsistent results were reported.

Thomas *et al* [110], used productivity and production data from 65 construction labour-intensive activities to determine the best predictive model amongst the straight-line, cubic and exponential learning curve models. Data were gathered from the construction of multi-storey residential structures, a six-storey apartment building and the fabrication and erection of a pre-cast segmental bridge. Based upon the results of their study, it was found that although the straight-line model has the advantage of simplicity, it may not always be reliable since the learning rate, which is assumed to be constant in the straight-line model, is not necessarily a constant value. Moreover, and for the 65 activities evaluated, the cubic learning curve model consistently resulted in a higher coefficient of determination and was the most suitable in modelling the effects of prior acquired experience and the levelling-off of man-hours at the end of the operation. However, it was concluded that much research is needed before reliable learning curve prediction models can be developed.

A similar study by Duff *et al* [27], found that the piecewise and cubic learning curve models provide better fit than the straight-line model. However, it was concluded that neither the piecewise nor the cubic learning curve models offer any tangible benefit in modelling the learning phenomenon for the generality of construction activities for which data had been collected.

In an attempt to measure the correlation between several previously untested models and historical data to determine which models provide the best prediction of time per cycle for future activities, another investigation was conducted by Everett and Farghal [30]. Historical data for 60 macro and micro-level construction field operations ranging from building entire houses to fixing pre-cast concrete panels were gathered and investigated, and the conclusion of this study was that the cubic models, in general, provide better correlation to historical data than linear models. However, despite their high correlation to completed activities, cubic models are poor predictors for future performance and should not be used to estimate performance beyond known historical data. On the other hand, the study further concluded that linear models are the most reliable predictors for future performance.

Thus, apart from the straight-line model, all the previously discussed learning curve models require certain parameters to be subjectively estimated in order to be quantified. Therefore, to conduct an objective investigation of the influence of learning curve theory on the labour productivity of the activities observed, the straight-line model will be selected to form the basis for the investigation of the applicability of learning curve theory to *in situ* reinforced concrete construction.

The mathematical formulas describing the straight-line learning curve model are presented and discussed in chapter five. For more detailed information and discussion of the Stanford "B", cubic, piecewise and exponential models, the reader is referred to Thomas *et al* [110].

2.7.3 Application of Learning Curve Theory in the Construction Industry

The learning phenomenon has proved applicable in various industries, especially those associated with mass productions such as, aircraft and automotive assembly, electrical, steel and glass manufacture, and petroleum refining. In such industries, the effect of learning was found to exist in the start-up, process-oriented contexts, job order production and the mature phases of production levels [25]. The learning process in labour-intensive industries, such as construction, is assumed to be more significant in the general sense that automated work is constrained by the fact that machines cannot benefit from previous experience and therefore would not "learn" to run any faster or increase the rate of production.

However, the application of the learning curve theory in the construction industry is accompanied by some concerns. On the one hand, construction tasks usually take place under different and unique site conditions. On the other, construction tasks are typically varied and non-repetitive, and workers may not have the opportunity to perform the same task repeatedly. That is one of the critical reasons why the construction industry shows rather low productivity in comparison with other manufacturing industries such as aircraft and automotive assembly.

Despite the negative response of the construction industry to the application of the learning curve theory, several previous research [25,30,110,111] proved the importance of its concept to construction productivity. In an attempt to quantify the effect of learning curve on formwork productivity of spandrel beams and elevator core walls in a multi-storey correctional facility in Seattle, Washington, Touran *et al* [111], using the straight-line learning curve model, found a significant productivity gains due to formwork repetition. At this stage however, an important distinction, which is of a particular importance to formwork productivity measurements, is the difference between the effect of activity or task and material repetitions on productivity improvement. Formwork productivity improvement results either from the saving achieved in measurement and forming inputs due to material repetition, or from the effect of the learning phenomenon as a consequence of repeating the same activity several times by the same labours. In this investigation, the first case was called the repetition factor, and the later was referred to as the learning phenomenon. In view of this discussion, upon investigating the effect of learning on formwork labour productivity, the input of the first cycle would be discarded from the analysis. The logic behind this approach stems from the possibility that any gain in labour productivity between the first and second formwork cycles might be the result of the combined effects; material repetition factor as well as the learning phenomenon. To unravel the effect of learning, the researcher suggests that, whenever the influence of material repetition may combine with the learning phenomenon, such as between the first two cycles and upon the replacement of forms due to wear after several use in multi-storey buildings, the labour input of such cycles should be discarded from the analysis.

Wideman, as reported by Dong [25], who applied the learning curve theory on the floor construction of an identical 25-storey concrete building, also arrived at the conclusion that the straight-line learning curve was useful in many practical applications, project management observation and control. Dong [25] investigated the learning effect on the construction productivity of eighteen housing projects and concluded an overall significant positive linear relationship between construction productivity and learning. Thomas *et al* [110], analysed productivity data from 65 different construction labour-intensive activities to model the effect of learning curve theory on construction productivity. The outcome of their study quantified high coefficients of determination for the relationships between time and cycle number. Everett and Farghal [30] investigated the impact of the learning on construction productivity of 60 construction field operations activities. The result of their investigation also quantified a high correlation between time and cycle number, and was concluded that the learning curve theory is a reliable tool for predicting historical as well as future performance.

Based on the preceding discussion, we may assume that the effect of learning on the construction labour productivity of *in situ* reinforced concrete recurring trades, i.e. floors formwork, fixing reinforcement in beams and slabs, and pumped concrete may be exhibited and may have a significant positive influence. The objectives of this investigation are to determine the applicability of the learning curve theory to reinforced concrete construction, and quantify its effect on the labour productivity of the previously mentioned trades.

2.8 Summary

In this chapter, the advantages of reinforced concrete material were highlighted. In addition, various buildability factors influencing the major trades associated with reinforced concrete construction, i.e. formwork, reinforcing steel, concreting and finishing were discussed. A wide variety of materials is used for all parts of formwork. The most common material however is timber, also known as "traditional" formwork. Timber has the advantage over all other materials because it can be easily cut, handled and assembled on site. Formwork labour productivity would be influenced by the type of material utilised. Consequently, in order to minimise such an influence, construction sites employing the traditional timber material for formwork will be selected for observation and data collection.

Cutting and bending as well as fixing reinforcing steel bars are two distinct activities. Therefore, the investigated labour productivity of reinforcing steel activity will be limited to the *in situ* fixing process, i.e. placing and tying reinforcing steel bars in positions. However, an activity such as reinforcing steel fixing is associated with difficulties in productivity measurement due to the variety of reinforcing steel bar diameters, consequently, the characteristic productivity concept will be used throughout the research project for labour productivity measurement of reinforcing steel trade.

The mechanisms of skipped and pumped concrete were introduced. On the other hand, the various finishing types used for concrete surfaces were explained. However, due to the difficulty in collecting representative sample sizes of the various finishing types, observation will focus on the power-trowelled finishing type.

The concept of buildability was presented. Several definitions of buildability were reviewed, and an extension to the available definitions, which introduced the total as well as partial factor buildability, was proposed. Furthermore, the importance of buildability and its influence on labour productivity were explained. Amongst other highlighted factors, the review has strongly indicated that buildability is a major influential factor on construction productivity. The only available buildability appraisal tool, the "Buildable Design Appraisal System", was described and its shortcomings discussed.

The importance of productivity to the construction industry was highlighted and factors influencing construction productivity were introduced. The various available techniques utilised in measuring construction productivity were discussed. Since several sites are to be observed simultaneously, the intermittent observation technique will be used throughout this research project for productivity monitoring and measurement.

The concept and various definitions of productivity were also discussed. Since the research project focuses on the influence of design buildability factors on labour productivity, the partial or single factor productivity will be used to quantify the labour productivity of the observed trades using equation 2.7.

Due to its accuracy, practicality and objectivity, the physical unit of measurement will be used to quantify the various outputs of monitored activities. Throughout this research, in quantifying the labour productivity of the monitored activities, the numerator of equation 2.7 expresses the actual physical observed outputs whereas, the denominator is the productive man-hours associated with the observed outputs.

Finally, the learning curve concept, theory and basic available models were reviewed and discussed. Due to its simplicity and objectivity, the straight-line model will be selected for the investigation of the applicability of learning curve theory to *in situ* reinforced concrete trades, i.e. formwork, reinforcing steel and concreting.

Chapter Three

Development of Hypotheses

3.1 Introduction

The objective of this chapter is to present the buildability factors hypothesised to have an influence on the labour productivity of each trade of *in situ* reinforced concrete construction. The logic behind each hypothesis is explained, the various methods used to quantify the outputs of the observed activities are clarified, and the basis for investigating the effect of learning curve theory on the labour productivity of the relevant activities is presented.

3.2 Buildability Factors Hypothesised to Influence Productivity

Previous research, site observation, interviews with site management and gang members, and experience identified potential buildability factors which might be of a direct influence on labour productivity of *in situ* reinforced concrete trades.

Buildability factors such as grid patterns of footings and columns [8], structural framing types [21,34,91], geometry and dimensions of elements [4,34,50,99,100], height of floors [34], the degree of design rationalisation, standardisation and repetition [8,24,25,34,40,44,64,73,81,87,94,99,104], reinforcing steel quantity and diameters [4,34,50], location and congestion of reinforcement [4,50,76,94] are expected to have direct influence on the labour productivity of formwork and reinforcing steel trades. Volume and the specified workability of concrete, as well as the height of floors relative to the ground level, are also expected to affect the labour productivity of the concreting trade [11,90]. Trowelled area and the number of machines used in the process might have an impact on the labour productivity of the finishing activity. Based on the previous discussion, a set of buildability factors was hypothesised to impact the labour productivity of the relevant monitored activities within the observed trades.

Buildability factors hypothesised to influence the labour productivity of the observed activities are presented in a table format. A discussion on each factor and the logic behind its hypothesised effect on productivity follows. However, since several factors are common amongst the various observed activities, and in order to avoid repetition whenever the same hypothesis is encountered, hypotheses which are common amongst the observed activities are introduced and discussed first.

In the following tables, a distinction is made between the two levels of observation; macro and micro. As was previously explained in chapter two, at the macro-level observation, the observed input comprises the total productive time used to achieve the total physical output of the monitored activity, i.e. direct and contributory inputs [4,18,50,103]. At the micro-level observation, only direct productive input applied to achieve the output of an observed individual element within the activity is observed. Therefore, contributory inputs such as, setting-out, reading plans and identifying element locations have negligible influence on micro-level productivities. Finally, the expressions used to quantify formwork outputs of the various monitored elements are presented.

3.2.1 Buildability Factors Influencing Formwork Productivity

Sites observation focused on formwork for isolated and raft foundations, ground beams and slabs, columns, walls, and suspended floors. These activities were observed at the macro level, and where the activity comprised elements which could be monitored individually, i.e. isolated foundations, columns, beams and slab panels, micro-level observation was also conducted. The following tables highlight the buildability factors hypothesised to have an influence on formwork labour productivity of the various activities observed, followed by the developed hypotheses.

Table 3.1 Buildability Factors Influencing Formwork Productivity of Isolated Foundations

Macro-Level Observation
Grid Pattern
Variability of footing sizes
Total shutter area of footings
Average shutter area of footings
Micro-Level Observation
Shutter area of the observed footing

Table 3.2 Buildability Factors Influencing Formwork Productivity of Base Slabs

Macro-Level Observation
Total shutter area of edge forms
Geometric factor

Table 3.3 Buildability Factors Influencing Formwork Productivity of Ground Beams

Macro-Level Observation
Variability of beam sizes
Total shutter area of beams
Total Number of beam intersections
Micro-Level Observation
Shutter area of the observed beam
Number of intersections within the observed beam

Table 3.4 Buildability Factors Influencing Formwork Productivity of Columns

Macro-Level Observation
Grid pattern
Variability of column sizes
Repetition factor
Total shutter area of columns
Average shutter area of columns
Percentage of circular columns
Micro-Level Observation
Shutter area of the observed column
Geometry of the observed column

Table 3.5 Buildability Factors Influencing Formwork Productivity of Walls

Macro-Level Observation
Total shutter area
Geometric factor

Table 3.6 Buildability Factors Influencing Formwork Productivity of Suspended Floors

Macro-Level Observation
Variability of beam sizes in floor
Repetition factor
Floor area
Average slab panel area
Total number of beam intersections in floor
Beam-Floor ratio
Percentage of curved beams in floor
Percentage of non-rectangular slab panels in floor

Table 3.7 Buildability Factors Influencing Formwork Productivity of Suspended Beams

Micro-Level Observation
Repetition factor
Shutter area of the observed beam
Number of intersections within the observed beam
Geometry of the observed beam span

Table 3.8 Buildability Factors Influencing Formwork Productivity of Suspended Slab Panels

Micro-Level Observation
Repetition factor
Area of the observed slab panel
Geometry of the observed slab panel

1. Formwork Area

A common hypothesis amongst all monitored activities is that a positive relationship between labour productivity and formwork area exits.

The logic behind this hypothesis is fourfold. First, an initial contributory time is required by gang members to prepare work areas and formwork materials prior to commencing the direct or effective work. Therefore, if an activity is of a small-scale type, a major portion of the total input is directed towards contributory rather than effective work. Second, and of special importance at the micro-level, we hypothesise that it takes about the same input to fix the shutter for instance, of a 300 x 300 mm column as for 500 x 500 mm. This hypothesis applies equally for all single elements monitored in this research. Third, when gang members are confronted with large scale activities, better preparation, planning and control is applied on sites, and finally, in large scale monitored activities, the observer noticed that gang members tend to work harder and take less frequent breaks. In view of the preceding discussion, we would refer to such an effect as "economy of scale", and hypothesise a positive relationship between labour productivity and formwork area.

Activities such as isolated foundations, columns and slab panels, are composed of individual finite elements of different shutter areas. The total shutter area recorded at the macro-level observation of any of these activities is the sum of the shutter areas of its individual constituents. Thus, holding all other variables constant, we may, theoretically, expect a similar labour productivity between two sites having approximately the same formwork outputs regardless of the number of footings, columns or slab panels. In other words, if a site has for instance, forty small size footings, and another has twenty medium to large size footings, and if we further assume that the formwork output of footings is approximately the same on both sites, then we would expect the labour productivity to be similar on both sites. However, this assumption is not necessarily true, and we would expect higher labour productivity on the later site.

We therefore hypothesise that the average size of individual elements, i.e. footings, columns and slab panels, is a variable which should be considered. The average size of isolated foundations, columns and slab panels respectively is mathematically quantified as follows:

$$\frac{\textit{Total shutter area of footings}\,(m^2)}{\textit{Total number of footings}}$$

$$\frac{\textit{Total shutter area of columns}\,(m^2)}{\textit{Total number of columns}}$$

$$\frac{\textit{Floor area}\,(m^2)}{\textit{Total number of slab panels within the floor}}$$

2. Variability of Element Sizes

Another common hypothesis amongst isolated foundation, column and beam activities observed at the macro-level is that a loss in labour productivity would be anticipated as the number of elements of different sizes increases. When the number of different sizes within the activity increases, additional contributory input is directed towards setting-out, reading plans and identifying element locations. It is hypothesised that design rationalisation and standardisation, as practically as possible, of element sizes within the activity would minimise such contributory input and enhance the site efficiency. The total number of different element sizes used within the monitored activity is used to quantify the variability of element sizes.

3. Formwork Repetition of Elements

We also hypothesise that formwork repetition of elements leads to a gain in labour productivity. Inputs of formwork activities include substantial amount of laborious measurements and cuttings to required sizes and shapes. Consequently, the repetition of elements within and between stories in activities such as columns, beams and slabs would minimise such inputs and increase labour productivity. However, unlike the activity of beams where sides and soffits are assembled during the activity process, column sides are made and stacked in advance and before the activity commences. When the column activity is ready to start, pre-assembled sides are transported and fixed in place. Consequently, the repetition effect of the physical dimension on formwork labour productivity of columns is of an influence only at the macro-level observation of the activity.

The repetition criterion, i.e. whether or not the forms of the monitored elements are erected for the first time, will be treated as a categorical or binary variable to quantify the average difference in labour productivity between the two categories. In other words, a binary relationship is assumed: the variable is either present or not. Categorical variables are discussed in chapter five.

4. Grid Pattern

We hypothesise that axes layout or grid pattern has a direct impact on setting-out labour productivity of isolated foundation and column activities. In contrast to scattered and irregular positioning, a uniform and symmetrical grid pattern facilitates setting-out maximum number of footings or columns with minimum axes and measurements, therefore, accelerates the setting-out activity. In order to determine the impact of grid pattern on setting-out productivity of footing and column activities, a mathematical relationship was devised and expressed as follows:

$$\textit{Labour productivity}\ \alpha\ \frac{\textit{Total number of footings or columns}}{\textit{Total number of footing or column axes}}$$

The logic behind the relationship shown above stems from applying the concept of standardisation. Uniform and symmetrical grid patterns of footings and columns are set-out using minimum number of axes or grid lines. Therefore, as the ratio of the total element number to the total axes number increases, we can reasonably conclude that uniformity and symmetry of the grid pattern increases too. Figure 3.1 illustrates this concept.

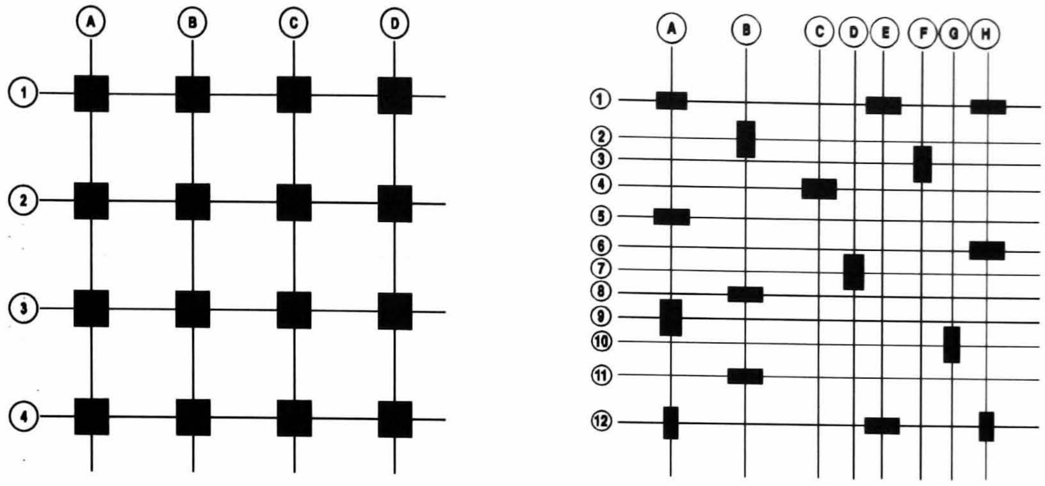


Figure 3.1 Uniform and Symmetrical Versus Scattered and Irregular Grids

5. Intersection of Beams

Intersection of beams occurs when a beam frames onto another beam. This situation is frequent in both ground and suspended beams. When encountered, a joint or opening having the same dimension of the supported beam must be formed in the supporting beam at the location of the intersection. When a beam is supporting one or several beams, especially if the supporting and supported beams differ in depth, additional input is required for measurement, cutting and fixing supporting beam sides. Therefore, due to the lack of standardising the activity, we would hypothesise a negative relationship between the number of joints or intersections in beams, i.e. total number of supported beams along the sides of the supporting beams, and formwork labour productivity of the supporting beams. Figure 3.2 depicts a formwork joint at beams intersection.

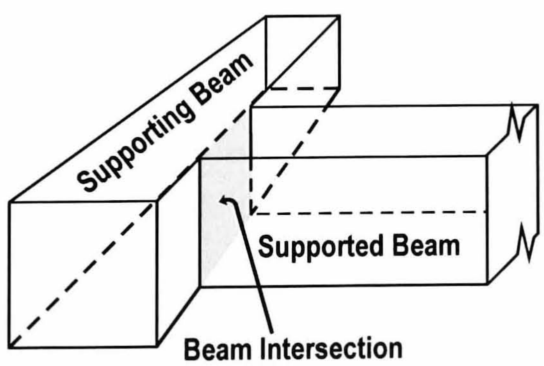


Figure 3.2 Formwork Joint at Beams Intersection

6. Perimeter Geometry

Based on the effects of design rationalisation and standardisation, we would expect higher formwork labour productivity in base slabs and walls as the number of angles around the perimeter decreases. The activity would be much simpler and faster when carpenters fix edge forms or wall shutters with minimum interruption resulting from constantly changing directions along the perimeter. In addition, as the number of angles increases, more measurement, cutting and corner alignment is required. Figure 3.3 illustrates this principle.

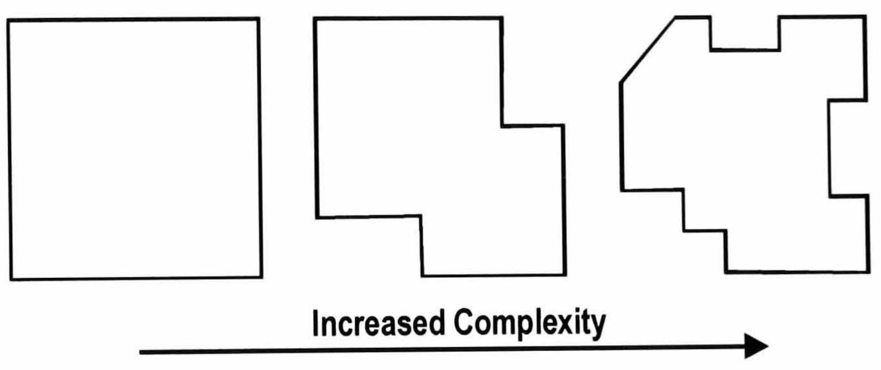


Figure 3.3 Number of Angles around the Perimeter

The influence of perimeter geometry on labour productivity is characterised by the following expression:

$$\textbf{\textit{Geometric factor}} = \frac{\textbf{\textit{Total number of angels around the perimeter}}}{\textbf{\textit{Total perimeter length (m)}}}$$

We would therefore hypothesise that as the value of the geometric factor increases, labour productivity decreases.

7. Column Geometry

The effect of design simplicity on labour productivity would be further investigated in formwork activity of columns. Shuttering circular columns using traditional formwork involves making round shapes form, usually 50 mm wide timber boards. Such boards are assembled next to one another until the circle is complete. Specially fabricated, usually off-site, semi-circular moulds placed face to face on each side of the column are used to hold the timber boards in position. Following this laborious task, each half of the column is transported to the required location and erected. Because of the complexity associated with the curved shutters, we hypothesise that a loss in labour productivity will occur when any of the floor columns are circular. We further hypothesise that the intensity of the loss in macro-level labour productivity is a function of the percentage of circular columns in floor. The percentage of circular columns in floor is quantified as follows:

$$\frac{\textit{Total shutter area of circular columns}\,(m^2)}{\textit{Total shutter area of all columns}\,(m^2)} * 100$$

On the other hand, to quantify the average difference in formwork labour productivity between circular and rectangular columns observed at the micro-level, a binary variable indicating the geometry of column and quantifying the average difference in labour productivity between shuttering circular and rectangular columns will be used.

8. Floor Framing System

We hypothesise that flat plate floors are easier to build than the beam-slab types because the shuttering is simpler. Since the end user of the floor or the client is effectively paying for the "usable" floor area regardless of how this area is structurally framed or supported, the formwork labour productivity of this activity is assessed using the usable floor area and not the total shutter area used to form the floor. Consequently, incorporating beams into the framing plan of the floor would automatically yield a loss in labour productivity. In other words and simply stated, there is an additional input in the activity which is not associated with or accounted for in the physical output. Figure 3.4 illustrates this concept.

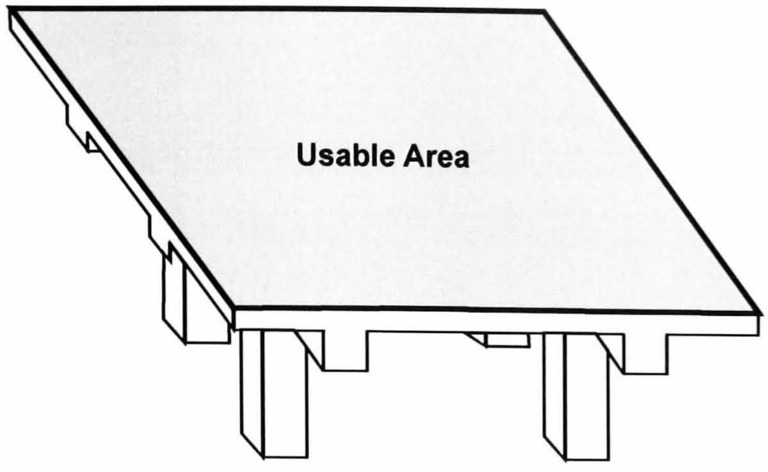


Figure 3.4 The Usable Area Concept

The intensity of labour productivity loss however depends on the number of beams used to support the floor. Figure 3.5 illustrates the beam-slab framing system.

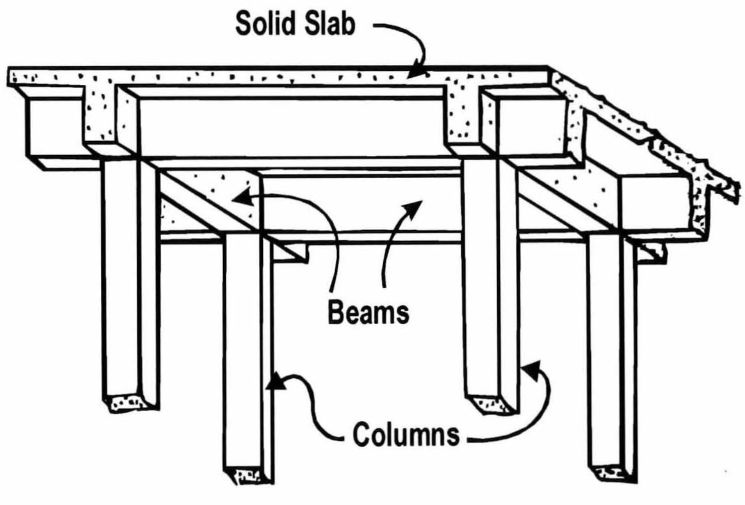


Figure 3.5 Beam-Slab Framing System

In order to quantify the influence of the presence of beams on macro-level formwork labour productivity, the Beam-Floor Ratio variable was introduced and expressed as follows:

$$\frac{\textit{Total shutter area of beams in floor}\ (m^2)}{\textit{Total "usable" floor area}\ (m^2)}$$

In view of the previous discussion, we would expect an increase in formwork labour productivity as the Beam-Floor Ratio decreases.

9. Beam and Slab Geometry

Curved beams present challenging tasks to formwork gang members. The input of a curved beam involves setting-out the curved span based on the designated radius, cutting soffit to the required shape and size, securely fixing forms in place and bracing. We would therefore hypothesise that formwork macro-level labour productivity will decrease as the percentage of curved beams in a floor increases. The percentage of curved beams in a floor is quantified as follows:

$$\frac{\textit{Total shutter area of curved beams in floor}\ (m^2)}{\textit{Total shutter area of all beams in floor}\ (m^2)} * 100$$

Similarly, we hypothesise that the formwork productivity of non-rectangular slab panels will be lower than for rectangular slabs. Unlike rectangular panels, circular, trapezoidal and triangular panels, involve substantial additional input in measurement and cutting to the required size and shape. Therefore, we would expect a loss in macro-level labour productivity as the percentage of non-rectangular slab panels in the floor increases. The percentage of non-rectangular slab panels in the floor is expressed as follows:

$$\frac{\textit{Total shutter area of non} - \textit{rectangualar slab panels in floor}\ (m^2)}{\textit{Total shutter area of all panels in floor}\ (m^2)} * 100$$

In order to quantify the average difference in micro-level labour productivity between curved and linear beams on the one hand, and between non-rectangular and rectangular panels on the other, a categorical or binary variable will be used.

3.2.2 Physical Formwork Outputs of Monitored Elements

Formwork output, or shutter area, of a single isolated footing was quantified by multiplying the footing perimeter by the depth. Mathematically, it is expressed as follows:

$$(\textit{Width}\ (m) * 2 + \textit{Length}\ (m) * 2) * \textit{Depth}\ (m)$$

The total formwork output, or shutter area, of the activity is the sum of all shutter areas of single footings.

Total shutter area of a base slab was quantified by multiplying the total perimeter length by the edge depth, or:

$$\textbf{\textit{Total perimeter length (m)}} * \textbf{\textit{Edge depth (m)}}$$

The total formwork output of ground beams is the total sum of all shutter areas of single ground beams. Since ground beams are fixed directly on ground, only beam sides were used to quantify the formwork outputs. The shutter area of a single ground beam is therefore quantified as follows:

$$[\textit{Depth of beam side (m)} * 2] * \textit{Total span of beam (m)}$$

The total shutter area of rectangular and circular columns is the total sum of all shutter areas of single rectangular and circular columns. Rectangular and circular column shutter areas were quantified as follows:

$$\textit{Rectangular column shutter area } (m^2) = (\textit{Width (m)} * 2 + \textit{Length (m)} * 2) * \textit{Height (m)}$$

$$\textit{Circular column shutter area } (m^2) = (\pi * (\textit{Radius (m)})^2) * \textit{Height (m)}$$

Total formwork output of a double-sided wall with stop-end panels was quantified by its actual physical dimensions and expressed as follows:

$$[\textit{Length (m)} * \textit{Height (m)}] * 2 + [\textit{Width (m)} * \textit{Height (m)}] * \textit{Number of stop ends}$$

Formwork output of a suspended beam was quantified as follows:

$$[\textit{Beam side (m)} * 2 + \textit{Soffit width (m)}] * \textit{Beam span (m)}$$

The total shutter area of beams is the sum of all shutter areas of single beams in a floor.

Finally, the slab area is quantified according to its shape. The floor area is the total "usable" area of floor.

3.2.3 Buildability Factors Influencing Reinforcing Steel Productivity

The following tables present the buildability factors hypothesised to have an impact on reinforcing steel fixing labour productivity of the various activities observed, followed by the developed hypotheses.

Table 3.9 Buildability Factors Influencing Reinforcing Steel Productivity of Isolated Foundations

Macro-Level Observation
Variability of footing sizes
Characteristic bar diameter[1]
Total quantity of reinforcement fixed
Micro-Level Observation
Characteristic bar diameter fixed in the observed footing
Quantity of reinforcement fixed in the observed footing

[1]The Characteristic bar diameter is the reinforcing bar diameter which accounts for the majority of the quantity of reinforcement fixed.

Table 3.10 Buildability Factors Influencing Reinforcing Steel Productivity of Base Slabs

Macro-Level Observation
Characteristic bar diameter
Total quantity of reinforcement fixed
Geometry of slab
Micro-Level Observation
Characteristic bar diameter fixed in the observed layer
Quantity of reinforcement fixed in the observed layer (Bottom, Top)
Layer location (Bottom, Top)
Geometry of slab

Table 3.11 Buildability Factors Influencing Reinforcing Steel Productivity of Columns

Macro-Level Observation
Variability of column sizes
Characteristic bar diameter
Total quantity of reinforcement fixed
Percentage of reinforcement fixed in circular columns
Micro-Level Observation
Characteristic bar diameter fixed in the observed column
Quantity of reinforcement fixed in the observed column
Geometry of the observed column

Table 3.12 Buildability Factors Influencing Reinforcing Steel Productivity of Walls

Macro-Level Observation
Characteristic bar diameter
Total quantity of reinforcement fixed
Wall thickness

Table 3.13 Buildability Factors Influencing Reinforcing Steel Productivity of Beams

Macro-Level Observation
Variability of beam sizes
Characteristic bar diameter
Characteristic stirrup diameter
Total quantity of reinforcement fixed
Average width of beams
Average depth of beams
Percentage of reinforcement fixed in curved beams
Micro-Level Observation
Characteristic bar diameter fixed in the observed beam
Stirrup diameter fixed in the observed beam
Quantity of reinforcement fixed in the observed beam
Width of the observed beam
Depth of the observed beam
Geometry of the observed beam span

Table 3.14 Buildability Factors Influencing Reinforcing Steel Productivity of Slab Panels

Macro-level Observation
Average slab panel area
Characteristic bar diameter
Total quantity of reinforcement fixed
Percentage of reinforcement fixed in non-rectangular slab panels
Micro-Level Observation
Characteristic bar diameter fixed in the observed slab panel
Quantity of reinforcement fixed in the observed layer (Bottom, Top)
Layer location (Bottom, Top)
Geometry of the observed slab panel

1. Quantity of Reinforcement

As was previously hypothesised in formwork trade, large scale activities are associated with better planning and control than small scale activities. In addition, an initial contributory time is required by gang members to prepare work areas and identify locations of relevant reinforcement in store prior to commencing the direct or effective work. Consequently, if an activity is small scale, a major part of the total input is directed toward contributory rather than effective or direct work. Moreover, as the case with formwork activities, it was also noticed that gang members tend to exert harder effort and take less frequent breaks when confronted with such activities. Furthermore, a fixer would just as easily and within approximately the same time frame, place and tie for instance, similar number of 10 mm and 12 mm diameter bars. Due to the "economy of scale" effect, we would hypothesise that as the quantity of reinforcement increases, steel fixing labour productivity increases too.

2. Rebar Diameter

We hypothesise that the diameter of rebar is likely to have a direct impact on fixing labour productivity. As the bar diameter increases, for the same quantity of reinforcement, fewer number of bars need to be fixed. We therefore hypothesise a positive relationship between bar diameter and fixing labour productivity.

3. Variability of Element Sizes

The additional contributory input directed toward constantly reading drawings for details, and locating various size elements within an activity could be saved by applying the concept of design rationalisation. Consequently, we hypothesise that a negative relationship exists between steel fixing labour productivity and the total number of element sizes within the observed activity.

4. Slab Geometry

Unlike rectangular slab panels, where reinforcing steel bars are only of two different lengths, and in the special case of the square type where all bars have the same length, fixing reinforcing steel bars in non-rectangular slabs is associated with additional inputs directed toward searching for the "right" bar length amongst the variable stacked lengths. As a result, the application of the standardisation concept would result in higher labour productivity, and we would expect higher fixing labour productivity in rectangular compared to non-rectangular panels. At the macro-level, the effect of slab geometry is quantified by the expression:

$$\frac{\textit{Total quantity of reinforcement fixed in non-rectangular slabs (kg)}}{\textit{Total quantity of reinforcement fixed in all slabs (kg)}} * 100$$

At the micro-level, where fixing rebar in individual slabs is observed, the effect of slab geometry will be expressed by introducing a binary variable to indicate the shape of slab and quantify the average difference in fixing labour productivity between non-rectangular and rectangular slabs.

5. Reinforcement Layer Location in Slabs

Reinforcement in deep slabs is usually specified in double layers where bottom steel is fixed in two directions first, then steel chairs are used to support the top layer. Since the quantified output of the activity includes only the steel used to structurally reinforce the slab, the quantity of the chairs fixed is not included in the output. We hypothesise that the labour productivity of fixing the top layer reinforcement is lower than the bottom layer. The logic behind this hypothesis is threefold: first, the additional labour input used to fix the chairs does not contribute to the measurement of the top layer output; second, and unlike fixing bottom layer reinforcement which involves distributing and tying bars in place, top layer fixing involves lifting bars a distance approximately equal to the thickness of the slab prior to fixing; and finally, the mobility of the fixers is substantially reduced when they tie the top layer bars whilst standing on top of the reinforcement layer.

Macro-level observation of this activity involved the input to fix the total quantity of reinforcement in both layers, i.e. bottom and top. On the other hand, micro-level observation involved the input applied to fix each layer separately. As a result, in quantifying fixing labour productivity, the output of each layer, i.e. quantity of steel fixed, associated with the relevant productive input of each layer will be used. The influence of reinforcement layer location on fixing labour productivity will be revealed by introducing a binary variable to indicate the observed layer location and quantify the average difference in labour productivity between the two locations. Typical doubly reinforced slab arrangement is shown in figure 3.6.

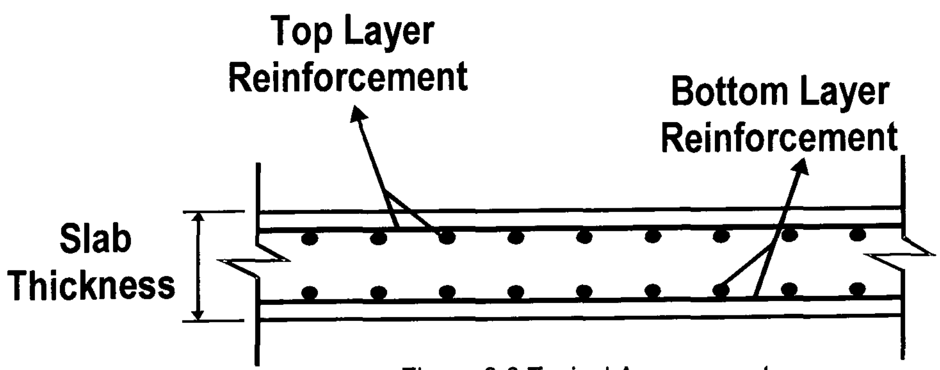


Figure 3.6 Typical Arrangement
of Slab Reinforcement

6. Column Geometry

We hypothesise that fixing reinforcement in circular columns is associated with higher labour inputs compared with rectangular columns. Unlike standardised rectangular columns where the longitudinal reinforcement on each side of the column is distributed collinearly, the circular arrangement of reinforcing bars requires additional labour input to evenly distribute the reinforcement around the perimeter as shown in figure 3.7.

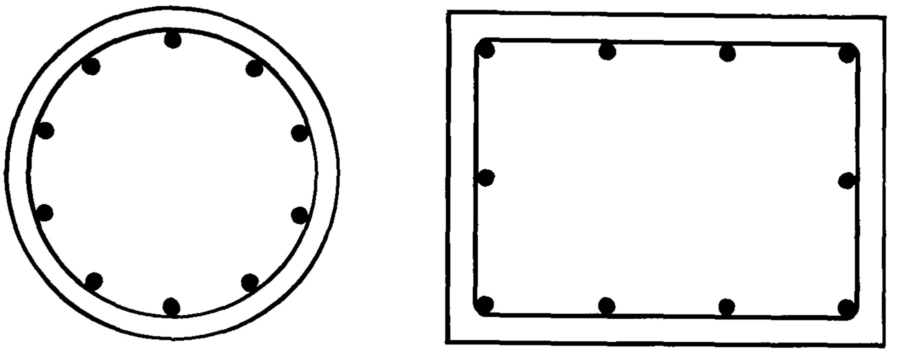


Figure 3.7 Typical Arrangement of Reinforcement in Circular and Rectangular Columns

At the macro-level, where the monitored activity might involve both types of columns, rectangular and circular, the relationship between labour productivity and column geometry is quantified by the following expression:

$$\frac{\textbf{\textit{Total quantity of reinforcement fixed in circular columns (Kg)}}}{\textbf{\textit{Total quantity of reinforcement fixed in all columns (Kg)}}} * 100$$

At the micro-level, the influence of geometry on fixing labour productivity of columns will be assessed by introducing a binary variable to indicate the shape of column and quantify the average difference in labour productivity between the two categories, i.e. circular and rectangular.

7. Wall Thickness

Wall reinforcement consists of vertical and horizontal bars placed and tied on each face of the wall. The fixing process involves placing and tying outer face reinforcement, i.e. the face directly facing the soil as the case for basement walls for instance, before the inner face reinforcement is fixed. During this process, vertical outer face reinforcement is placed first, and then horizontal steel bars of both faces are placed and tied to the vertical steel in a bundle of two bars on the outer face. In each bundle, outer face reinforcement is securely tied to vertical steel whilst the other bar is loosely tied as to just hold it in place. Following this step, inner face vertical reinforcement is placed in position, and the horizontal reinforcement previously held by loose ties on the outer face vertical reinforcement is shifted to the inner face of the wall and securely tied to the inner face vertical reinforcement. A typical wall reinforcement arrangement is shown in figure 3.8.

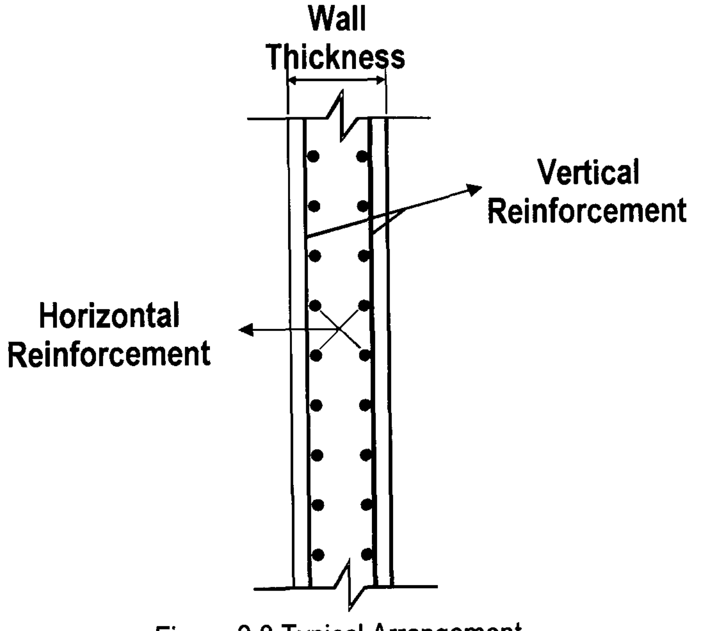


Figure 3.8 Typical Arrangement of Wall Reinforcement

We would hypothesise that there is a positive relationship between wall thickness and fixing labour productivity because the space for manipulating the bars is less as the distance between both reinforcement layers is reduced.

8. Beam Geometry

Reinforcement in beams consists of longitudinal and transverse steel. Longitudinal bars are placed at top and bottom faces, whereas transverse steel, i.e. stirrups, are placed at right angle to the longitudinal reinforcement. Usually, when the depth of beams exceeds 700 mm, side or skin reinforcement is placed down each side. Figure 3.9 shows a typical reinforcement arrangement in beams.

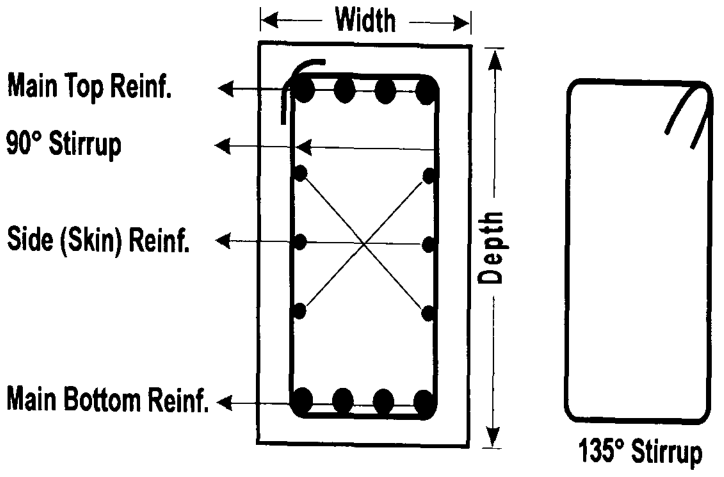


Figure 3.9 Typical Beam Reinforcement Details

Fixing reinforcement in linear beams involves hanging top bars right on top of beam formwork moulds, inserting stirrups, placing the bottom face reinforcement, and when required, skin reinforcement, evenly distributing bars in positions, securely tying longitudinal to transverse reinforcement, and finally placing the reinforcement cages in the formwork by detaching the cage supports. Since all monitored sites used closed type stirrups in beams, inserting such stirrups involved forcing the two open-ended sides away from each other and inserting the stirrup so that top bars are inside the loop.

The fixing process of curved beams is different. Due to the difficulty in inserting curved longitudinal bars using the previously discussed mechanism, all curved longitudinal reinforcing bars, i.e. top, side and bottom, are placed at the surface of formwork moulds. Top and bottom reinforcement however is separated using temporarily separators inserted at right angles to the beam spans. Stirrups are inserted by the same mechanism used in linear beams, however when the stirrups are in place, all reinforcement lies inside the loop towards the upper face of beams whilst stirrups are hanging loose inside the moulds at the bottom face of beams. When all stirrups are inserted, fixers withdraw the separators so that the bottom reinforcement falls inside the bottom sides of stirrups, and reinforcement cages lie inside the formwork moulds. Following this step, longitudinal bars get evenly distributed and securely tied with stirrups. Due to the difference in fixing process between the two categories of span geometry, we hypothesise that fixing labour productivity is higher in linear than in curved beams.

At the macro-level, the effect of curved beams on fixing labour productivity is quantified using the following expression:

$$\frac{\textit{Total quantity of curved beams reinforcement fixed in floor (kg)}}{\textit{Total quantity of reinforcement fixed in all beams in floor (kg)}} * 100$$

The difference in average fixing labour productivity between curved and linear beams observed at the micro-level will be quantified by using a binary variable indicating the span type and quantifying the average difference in fixing labour productivity between curved and linear beams.

9. Stirrup Diameter

Given the fact that the stiffness of a reinforcing bar increases as the diameter increases, and based on the previously explained mechanism of inserting stirrups in beams, we hypothesise that fixing 8 mm in diameter stirrups is more productive than fixing 10 mm stirrups in both types of beams, i.e. linear and curved.

It is important to note that the process of fixing steel in columns is different from that of beams. In columns, the reinforcement cage is fabricated using a platform where longitudinal bars are placed open-ended horizontally and links or ties are threaded on to the longitudinal bars and securely tied. The fabricated column cage is then lifted and fixed in position. Consequently, the diameter of column links should not have an effect on fixing labour productivity of columns.

The influence of characteristic stirrup diameter on steel fixing labour productivity of beams will be explored by introducing a binary variable indicating the characteristic diameter and quantifying the average difference in labour productivity between the two diameters encountered, 8 mm and 10 mm, at both observation levels, macro and micro.

10. Beam Width

We further hypothesise that there is a negative relationship between fixing labour productivity and the width of a beam. As the beam width increases, usually multi-leg stirrups are specified. Due to the complexity associated with stirrups fixing as we have previously discussed, installing multi-leg stirrups in beams might make the fixing process more difficult and mask any gain in labour productivity achieved from the total quantity increase.

11. Beam Depth

As the beam depth increases, side or skin reinforcement is distributed down both sides of the beam. This reinforcement is fixed in small quantities compared with main longitudinal reinforcement and does not contribute much to the overall quantity of steel, yet involves an additional input to ensure that it is evenly distributed along the sides and properly tied to beam stirrups. As the beam depth increases, potentially introducing an added difficulty for fixers to handle and insert rebar in place. Furthermore, and is of particular importance in curved beams where the reinforcing bars are distributed and fixed inside the formwork moulds as we have previously indicated, increasing beam depth may also result in lower fixing labour productivity. We therefore hypothesise that there is a negative relationship between steel fixing labour productivity and depth of beams.

At the macro-level, the average beam dimensions will be used to investigate the separate effects of width and depth on steel fixing labour productivity, whereas, the actual dimensions of beams observed at the micro-level will be used.

12. Discontinuity of Slab Panels Reinforcement

When reinforcement is specified discontinuously in slab panels, i.e. the reinforcement fixed in one slab panel does not extend to the adjacent panels due to difference in reinforcement details, the reinforcement of each panel is fixed separately. When the number of such discontinuous panels increases in the floor, additional contributory input is required to read the reinforcement details for each panel, which may disrupt the continuity and slow down the fixing process. In view of this, we hypothesise that a negative relationship exists between steel fixing labour productivity and the total number of discontinuous slab panels in the floor.

In order to reveal the influence of the discontinuous panel numbers in the floor, the average panel area is quantified as follows:

$$\frac{\textit{Total area of slab panels in floor } (m^2)}{\textit{Total number of discontinuous slab panels in floor}}$$

As the average panel area in the floor increases, fewer panels are encountered, and higher steel fixing labour productivity is expected.

3.2.4 Physical Reinforcement Outputs of Monitored Elements

Outputs represented by the actual quantity of reinforcement fixed (kg), were quantified for all activities observed. When an activity was observed at the macro-level, the total quantity fixed was collected from the gang leader and verified by the observer based on the relevant details shown on the drawings. Quantities fixed in elements observed at the micro-level were taken-off by the observer directly.

The method for taking-off reinforcement quantities involved using the relevant bar diameter, tabulated standard weights of reinforcing bars and length of fixed bars.

3.2.5 Concreting and Trowelling

A. Concreting

It is important to note that the monitored concreting activity comprised two distinct placement methods; pumped and skipped. Due to the difference between the elements cast by the two different methods, i.e. shape factor, a meaningful comparison between skipped and pumped concrete is not possible [11]. The collected data will therefore be analysed separately in order to validate the results.

The following table presents the buildability factors hypothesised to affect both pumped and skipped concrete labour productivity, followed by the developed hypotheses.

Table 3.15 Buildability Factors Influencing Pumped and Skipped Concrete Productivity

Volume of concrete placed
Height relative to ground level
Steel congestion ratio
Concrete workability (High, Medium, Low)

1. Concrete Volume

We hypothesise that large volume placements are associated with higher placing rates. The logic behind this hypothesis is fourfold. First, large volume placements are more likely to be thoroughly planned and prepared by gang members; second, concrete suppliers usually treat large volume orders as more seriously which would minimise delays in material supply; third, due to limited available hours during the working day, gang members tend to work harder so that the activity is completed within normal working hours; and finally, the initial contributory time required by gang members to prepare the work area prior to commencing the effective concreting work would be overshadowed by the effective or direct input.

2. Height Above Ground Level

Pours which are above ground level are expected to take longer than those near or at ground, and this is particularly significant in skipped concrete where the vertical travelling time of skips is a function of height. On the other hand, pumped concrete might also be affected by height since the boom movement flexibility gets substantially reduced as the vertical height of the concreted area increases. Furthermore, the coordination between the crane operator and his guide is markedly reduced as the height increases. We therefore hypothesise that a negative relationship exists between concreting labour productivity and height above ground level.

3. Concrete Workability

A major task in concreting activities is the compaction and consolidation of placed concrete. Compaction and consolidation are important to eliminate voids and entrapped air, and to effectively distribute concrete around reinforcement and into corners of formwork moulds. Compaction and consolidation of placed concrete is achieved using immersion or poker vibrators. Vibrators are inserted into the fresh concrete surface as far as possible and at close intervals to ensure even compaction and consolidation. Concrete workability as previously defined in chapter two is "the amount of mechanical work or energy required to produce full compaction and consolidation of fresh concrete without segregation" [70]. The steel congestion ratio on the other hand, is defined as "the total quantity of reinforcement contained in the concrete volume". We therefore hypothesise that more energy and additional input for compacting and consolidating concrete is needed as the workability of the mix decreases, and the steel congestion ratio increases.

Concrete workability is measured on site by the slump test [106]. In order to explore the effect of workability on concreting labour productivity, a binary variable will be introduced to indicate the workability of the observed pours and to quantify the average difference in labour productivity amongst the three different categories of workability; high, medium and low.

According to the slump values specified by the American Concrete Institute [10], and based on the researcher's previous site experience, a workable concrete mix design usually has a slump value ranges from 80 mm to 120 mm. In order to classify the concrete workability into a consistent scheme, the field experience of several concrete gang members was further sought. An almost unanimous feedback categorising the workability of concrete into three classifications; high, medium and low was obtained. Therefore, the workability classification scheme shown in table 3.16 will be used throughout this research project.

Table 3.16 Concrete Workability Classification

Specified Concrete Slump	Workability Classification
Slump greater than 120 mm	High
80 mm $\leq$ Slump $\leq$ 120 mm	Medium
Slump less than 80 mm	Low

B. Power-Trowelling

When a trowelled surface finish was specified, the trowelling activity was monitored separately. As soon as the concreted floor is hard enough for the trowelling activity to commence, power-trowelled machines ranging in diameters from 800 to 1000 mm and equipped with revolving float blades are used directly on the concrete surface. Each machine is driven by a single operator who concentrates on a specific area of floor in evenly distributed motions to ensure effective and uniform surface finish. When the trowelled area is large, several machines would be used simultaneously within the single floor. Due to the effect of the "economy of scale" previously discussed, we hypothesise that large trowelled areas are associated with thorough planning, control and harder effort from machine operators. In addition, the contributory time needed for preparation and cleaning up constitutes a smaller percentage of the total time for trowelling large floor areas. Consequently, we hypothesise a positive relationship between power-trowelling productivity and floor area.

Strictly speaking, the total number of machines employed in the activity is not a buildability factor, but rather depends on decisions made by the site management. However, the total number of machines utilised in the activity depends upon the floor area. As the floor area increases, more machines would be needed in order to complete the activity efficiently and within a reasonable time frame. Therefore, and provided that an adequate number of machines is used, we would further hypothesise that the efficiency of the activity would be positively influenced by the number of trowelling machines employed in the activity. The factors hypothesised to influence power-trowelling productivity are summarised in table 3.17.

Table 3.17 Factors Influencing Power-Trowelling Productivity

Area of the trowelled floor
Number of trowelling machines used in the activity

3.2.6 Physical Outputs of Monitored Concreting Activities

Outputs of concreting activities were quantified by the total volume of concrete poured. Concrete volumes were obtained directly from concreting records submitted by concrete suppliers to the site management. When the total concrete volume involves monitoring several different elements, e.g. suspended floor and ground slab cast during the same concreting activity, the volume of one element, usually the one with the uniform shape was measured directly by the observer using its actual physical dimensions, and discounted from the total volume placed to calculate the volume of the other element.

3.3 Investigation of Learning Curve Theory in Reinforced Concrete Construction

As was previously discussed in chapter two, the learning curve concept stems from the observation that individuals who conduct repetitive tasks exhibit an improvement in performance as the task is repeated several times. Previous research and experience have shown that activity repetition can affect and improve labour productivity, and designers can reduce labour costs by creating repetition on the job [25,30,110,111].

Based on the five basic mathematical models for learning curves previously presented and discussed in chapter two, the unit straight-line learning curve model was selected to form the basis for the investigation in this research. This model has the advantage of simplicity on the one hand, and is the most commonly used model for construction activities on the other [110]. The straight-line model is so called because it transforms to a straight line when plotted on a natural log-log scale.

The investigation into the applicability of learning curve theory, using the unit straight-line model, will be conducted on formwork, reinforcing steel fixing and concreting trades. Multi-storey buildings having identical repeated floors within each building were selected for this investigation. The effect on labour productivity due to learning will be assessed by the change in man-hours as the cycle or sequence number of the floors increases. The man-hours for each recurring cycle or floor were collected from all monitored projects and transformed into natural logarithms. All relevant data were then partitioned according to the projects and trades observed.

3.3.1 Formwork Investigation

Twenty-one different multi-storey buildings were selected for this investigation. The number of identical floors in each monitored building varied from a minimum of four to a maximum of ten, with an overall average cycle number of six for all observed buildings. In each monitored building, the total input of each recurring floor was collected upon the completion of the activity. In order to minimise the effect of delays on learning curve pattern, productive inputs, previously defined in chapter two, will be used in the investigation.

We have previously hypothesised that the repetition of elements is associated with higher labour productivity due to the savings in measurement, cutting and assembling materials to the required shapes and sizes. Furthermore, and according to the learning curve theory, we would hypothesise that learning, due to repetition of activities or tasks, might also have a positive influence on formwork labour productivity. Consequently, both phenomena can occur in a single observed floor. The question then would be: is the productivity increase due to saved input in forming or learning? The answer is, most probably a combination of both. How then do we separate the effect of learning? Unfortunately, we can not if both phenomena coexist. However, a simple solution to this dilemma would be to just discard the input of the first cycle from the analysis. The logic behind this solution stems from the observation that the effect of material repetition on formwork productivity is most noticeable between the first two floors and whenever formwork material is replaced within the same building. Therefore, if we discard the input of the first cycle and investigate the cycles thereafter, then it would be reasonable to assume that any decrease in the activity input as the cycle is repeated, would be due to the learning effect.

The final step before conducting the investigation was screening and partitioning the collected data. Upon the completion of the activity, the total productive input, i.e. man-hours, of each floor was cross-checked with a different gang member. Following this step, inputs and their corresponding floor or cycle numbers for each observed building were transformed into natural logarithmic values. As we have previously indicated, observation started from the second floor cycle, and when the formwork material was replaced in a certain floor, the cycle was ended at the previous floor. Following the discarded input of the floor in which forms were replaced, a new cycle was started.

3.3.2 Reinforcing Steel Investigation

The twenty-one different multi-storey buildings selected for the formwork investigation will also be used for the investigation of this trade. Unlike the formwork investigation however, all floors or cycles in the observed buildings will be included in the analysis. Since fixing reinforcement in beams precedes slabs, inputs of fixing beam and slab reinforcement in each recurring floor were collected separately upon the completion of each activity. Amongst the observed buildings, the number of monitored cycles varied from a minimum of five to a maximum of eleven for beams activity, and from a minimum of four to a maximum of eleven in slabs activity, with an overall average cycle number of seven for both activities in all observed buildings. In an effort to minimise the effect of delays on learning curve pattern, again, only productive labour inputs of both activities will be used in the investigation.

As with the formwork investigation, inputs and cycle numbers were transformed into natural logarithmic values to be used in plotting the unit log-log straight-line learning curve models.

3.3.3 Concreting Investigation

The same buildings selected for formwork and reinforcing steel fixing investigations will be also used for this investigation. The number of monitored cycles varied from a minimum of four to a maximum of ten, with an overall average cycle number of seven for all monitored buildings.

Data were collected either immediately after the completion of the concreting activity, or the day after. Again, delays experienced during floor concreting will be discounted and productive inputs will be used in the investigation. Inputs as well as cycle numbers were transformed into logarithmic values to be used in the unit straight-line model investigation.

3.4 Summary

Buildability factors hypothesised to influence the labour productivity of formwork, reinforcing steel fixing and concreting trades were discussed and the logic underlying the hypothesised effect of each factor was explained. The methods used to quantify the outputs of the various elements and activities monitored within each observed trade were illustrated. The concept of learning curve theory was introduced and the data collection procedure used in the investigation of the theory in relation to reinforced concrete trades was highlighted. The unit straight-line learning curve model was chosen as the basis for investigating the effect of learning on recurring activities due to its simplicity and universal applicability to most construction activities.

Chapter Four

Data Collection Methodology

4.1 Introduction

In order to achieve reliable and accurate productivity measurements, and to quantify the relationship between labour productivity and buildability factors, data must be collected in a systematic and consistent method from all monitored construction sites.

The objective of this chapter is to present the data collection methodology employed in this research. Pre-designed data collection forms are outlined, methods of construction and sites observation are illustrated and an efficient frequency for data collection is determined. Finally, screening of data and the coding system used in this research are explained.

4.2 Data Collection Forms

Specifically designed data collection forms were used in all observed construction sites. The main purpose of these forms was to consistently record the essential productivity parameters of inputs and their associated outputs for the various observed trades, and to reflect, to a large degree, the actual conditions on sites. A series of forms was carefully designed to include relevant information of each observed project. The site general information form included project type and number, effective starting date, space restriction, if any, normal daily working hours, and the site management level. In addition, a brief description of the observed project such as the contract procurement method, frame type, total floor area, and the number of stories was also included in the form. Finally, the characteristics of each observed trade were highlighted. The collection of such information was important to facilitate partitioning the data according to the research objectives and to spot check factors, other than buildability, which might be also of an influence on labour productivity. A typical site general information form is shown in figure 4.1.

Productivity Data Collection Form
Site General Information

Date: *5/4/03* Project No.: *0320* Form No.: A

1. **Site Management Level**

Position	No. of Personnel	Years of Experience
Project Manager	*1*	*20*
Site Engineer	*1*	*10*
Superintendent	*None*	*N/A*
Foreman	*2*	*25 & 20*

2. **Space Restriction:** *None*

3. **Other Restrictions:** *None*

(E.g. Power Cables Crossings, Restricted Access, etc.)

4. **Number of Normal Working Hours per Day:** *9.00*

5. **Project Description**

Project Type	No. of Stories	Total Floor Area (m^2)	Frame Type	Contract Procurement Method
Commercial Centre	*3*	*10,970*	*Reinforced Concrete*	*Lump Sum*

6. **Formwork**

Type	Storage	Gang/Crew Employment Method
Traditional Timber	☑On-Site ☐Off-Site	☐ Direct ☑ Subcontract

7. **Reinforcing Steel**

Storage	Fabrication	Gang/Crew Employment Method
☑On-Site ☐Off-Site	☑ On-Site ☐ Off-Site	☐ Direct ☑ Subcontract

8. **Concreting**

Type of Delivery	Casting Method	Workability	Type of Finish	Gang/Crew Employment Method
Truck Mixers	☑ Crane ☑ Pump ☐ Other	☐ High ☑ Medium ☐ Low	☐ Rough ☑ Leveled ☐Trowelled	☐ Direct ☑ Subcontract

Remarks:

Figure 4.1 Productivity Data Collection Form - Site General Information

Following the site general information form, site process information sheets for each observed trade were filled. These forms indicate the observed elements, labour source, major work procedures, and methods of transporting elements within the site. A selected typical site process information sheet is shown in figure 4.2.

Since productivity data were collected at both levels, macro and micro, it was important to design separate forms for each observation level. A macro-level data collection form for each activity within the trade was designed and cross-referenced by project number, form number, activity observed and the characteristics of the activity. Productivity parameters were explicitly recorded to express the total input and output of the monitored activity.

As was previously indicated in chapter two, macro and micro-level productivities of all observed activities were quantified using productive time. In order to quantify the productive input associated with the output of the activity, all encountered delays, whether avoidable or unavoidable, must be discounted form the total input. Therefore, to achieve the total productive input, all experienced delays within the monitored activity, their causes and types were recorded on the relevant data collection forms. Typical macro-level data collection form for the observed formwork trade is presented in figure 4.3.

Site Process Information Sheet
Formwork

Date	*20/1/03*	Project No.	*0302*	Form No.	F

Horizontal Elements

Please indicate all Elements that fall within this Category

Raft Foundation, Ground Beams, Ground Slab and Suspended Floors

Labour Source	☐Direct ☑Subcont.	Assembled	☑On-Site ☐Off-Site	Made	☑On-Site ☐Off-Site
Vertical Transport	☐Manual ☑Crane ☐Other		Horizontal Transport		☑Manual ☐Trailer ☐Crane ☐Other

Vertical Elements

Please indicate all Elements that fall within this Category

Walls and Columns

Labour Source	☐Direct ☑Subcont.	Assembled	☑On-Site ☐Off-Site	Made	☑On-Site ☐Off-Site
Vertical Transport	☐Manual ☑Crane ☐Other		Horizontal Transport		☑Manual ☐Trailer ☐Crane ☐Other

Other Elements

Please indicate all Elements that fall within this Category

Stairs

Labour Source	☐Direct ☑Subcont.	Assembled	☑On-Site ☐Off-Site	Made	☑On-Site ☐Off-Site
Vertical Transport	☐Manual ☑Crane ☐Other		Horizontal Transport		☑Manual ☐Trailer ☐Crane ☐Other

Remarks: ***Observation was limited to Horizontal and Vertical elements.***

Figure 4.2 Productivity Data Collection Form – Site Process Information Sheet

Macro-Level Productivity Data Collection Form
Formwork

Date: ***21/6/02*** Project No.: ***0209*** Form No: F-1

Element: ***Suspended Floor*** Location: ***1st Floor***

Forms Assembly: ☑ 1st ☐ Repeated (To be checked only in Columns & Floors)

Total Input to Complete the Activity (man-hours):

4 x 9.00 hr + 5 x 9.00 hr + 3 x 4.50 hr + 3 x 6.50 hr = 114.00

Total Output (m^2): ***248.00***

No. of Normal Working Hours per Day: ***9.00***

Cause of Delays	* Total Delays (Man-Hrs)	Type of Delays
Weather		☐ Interruption ☐ Disruption
Waiting for Materials		☐ Interruption ☐ Disruption
Construction Rework		☐ Interruption ☐ Disruption
Design Rework	***3 x 4.5 hr = 13.50***	☑ Interruption ☐ Disruption
Waiting for Tools		☐ Interruption ☐ Disruption
Waiting for Inspection		☐ Interruption ☐ Disruption
Waiting for Information		☐ Interruption ☐ Disruption
Waiting for Plant		☐ Interruption ☐ Disruption
Unbalanced Crew		☐ Interruption ☐ Disruption
Crew Interference		☐ Interruption ☐ Disruption
Crowded Work Area		☐ Interruption ☐ Disruption
Moving to New Work Location		☐ Interruption ☐ Disruption
Fabrication Rework Material Supplied		☐ Interruption ☐ Disruption
Others (Specify) 1.		☐ Interruption ☐ Disruption
2.		☐ Interruption ☐ Disruption
Total (man-hours)	***13.50***	

*Only Duration of Delays lasting longer than 1/4th of an hour for Interrupted activities and longer than One-half the work-shift for Disrupted activities shall be recorded.

Remarks: ***Design error in the dimensions of two beams was encountered.***

Figure 4.3 Macro-Level Formwork Productivity Data Collection Form

Since statistics vary from sample to sample, any inferences based on them will be subject to some uncertainty [97]. Thus, in order to judge the reliability of a sample statistic as a tool in making an inference about the corresponding population parameter, a sufficiently large sample of each activity observed has to be collected. Sincich *et al* [97] suggest a minimum sample size of 30. In view of this, to achieve valid and robust results on the one hand, and a reliable statistical significance on the other, it is important to maximise, as practically as possible, the number of productivity data points. This was achieved by collecting data at the micro-level in addition to the macro-level. Monitoring an activity at the micro-level would further assist us in a) triangulate the results; and b) understand the overall phenomena and patterns depicted from the macro-level observation of the activity.

Micro-level data collection forms were slightly different and simpler in their designs compared to the macro-level forms. Formwork and reinforcing steel micro-level data collection forms were similar in their format and included the reference code, i.e. element mark, element type as well as the relevant productivity parameters. The logic behind simplifying micro-level data collection forms, as much as possible, stems from the possibility that several forms might be filled by the same workers in a single workday. Selected micro-level data collection form is presented in figure 4.4 shown below. The complete set of data collection forms used throughout the data collection phase of this research project is presented in appendices A through I.

Micro-Level Productivity Data Collection Form
Formwork

Date: ***17/3/03***	Project No.: ***0303***	Form No.: F-1'
Element observed: ***Curved Beam***		Element Mark: ***B-103***
Starting Time: ***10:30 am***	Finishing Time: ***2:00 pm***	Delays: ***0.50 hr (Break)***
Total No. of Carpenters Worked to Complete the Activity: **2**		

Figure 4.4 Micro-Level Formwork Productivity Data Collection Form

4.3 Projects Description

The productivity data used in this research project were collected from thirty-nine different main projects over a total period of nineteen months. In addition to the main projects selected for observation, pre-selected activities and elements which are either non-repetitive in nature within the observed single site, or usually not frequently encountered on sites, were also monitored on several other sites to complement the required productivity data. Such activities and elements included foundations, ground beams and slabs, basement walls, curved beams, circular columns, non-rectangular slab panels and power-trowelled concrete surfaces. Moreover, and apart from the main observed projects, several multi-storey buildings characterised by recurring activities, were also selected for investigating the applicability of learning curve theory to reinforced concrete construction.

Due to the limited available reinforced concrete construction sites in Dundee and its surrounding areas, and in order to achieve the research objectives, the researcher decided to collect the required data for this study from the State of Kuwait, where the *in situ* reinforced concrete is the prevailing type of construction. The reason behind choosing this geographical location was twofold. First, the construction practice complies with most international codes of practice, especially, British and North American standards, and second, the researcher's familiarity with the construction industry due to his profession which facilitates access to various construction sites in that region. However, since the skill of the labour force is a major factor influencing labour productivity, and that such skills may vary across geographical regions, it is important to note that the findings derived from this study may be used to generalise the overall influence of the basic buildability principles on labour productivity, but not the results themselves in other contexts.

Projects monitored included residential and office buildings, commercial centres, industrial facilities and warehouses. The focus was on construction sites which shared, as much as practical, common features such as, contract procurement and construction methods, type and size. Another important factor which led to choosing certain sites over others was the accessibility and willingness of site personnel at both management and gang levels to cooperate with the observer. As far as possible, most of monitored projects were selected to be in close proximity to one another so that the observer can monitor several sites during the same day.

4.4 Methods of Construction

Regardless of the type of monitored projects, a similar pattern and sequence exists at the activity level and amongst the activities in reinforced concrete construction. The construction of sub-structural and structural reinforced concrete elements and frames involves the following three main trades:

a) falsework / formwork;

b) reinforcing steel fixing; and

c) concrete placing and finishing

Reinforced concrete buildings are composed of foundation system, columns/walls and slabs. Depending on the type and function of the building, other structural elements are also incorporated in the design such as ground and suspended beams.

It is important to recapture at this stage however on what we have previously discussed in chapter two concerning the different types and specifications of materials used in this type of construction.

A wide variety of materials is used for all parts of formwork, and each type has its own characteristics which might have an influence on the labour productivity of the trade. Therefore, it was important to select sites which utilised similar formwork materials. Since "traditional" formwork, also referred to as timber, is the most common material, this type of formwork was chosen for observation.

Observation of reinforcing steel fixing trade was limited to members in which their reinforcing bars were fabricated on site and fixed *in situ*. As we have previously indicated in chapter two, depending on the scale of the project and details of reinforcement, steel bars are delivered to sites either as straight bars in standard bundles, or cut and bent to sizes and shapes off site. Cutting and bending, and fixing of reinforcement are two distinct activities which may be performed by two different gangs on site. Thus, in this study, the investigation of labour productivity of reinforcing steel activity would be limited to the *in situ* fixing process, i.e. placing and tying reinforcing steel bars in positions.

In all observed projects, off-site ready mixed concrete delivered by truck mixers was used. In addition, the two most common methods for placing concrete, pumps and skips, were used in all monitored concreting activities.

The building construction proceeds with setting-out isolated foundation axes or perimeter layout in the case of the raft foundation type. Following the inspection of this step, the formwork activity of foundations is ready to start. Forms composed of plywood sheets, are vertically fixed, braced and secured in position. Upon inspection of formwork, reinforcing steel bars are placed and securely tied. The final step after reinforcing steel inspection is the concreting process of the activity.

After curing and insulating the placed concrete, backfill is compacted in layers to the specified level. At this stage, ground beams activity, if specified on the drawings, would proceed. Ground beams activity starts with setting-out the ground to the required levels. Following this step, plywood sheets used to make the two sides of beams, are securely fixed, tied and braced. Fixing longitudinal and transverse reinforcing steel follows, and after inspection, concreting proceeds.

After backfilling and compacting, the ground slab is ready for carpenters. Since the depth of most ground slabs, and depending on the function of this element, ranges from 100 mm to 300 mm, timber boards are usually used in the formwork activity. Boards are assembled on site to the required depth and usually fixed on the edge of the perimeter ground beams. Reinforcing steel bars are then placed and securely tied. Finally, after inspection, concreting takes place.

Once the ground slab concrete is cured, columns and walls activities proceed. This activity starts with setting-out axes as specified on the drawings. After the inspection and verification of column and wall axes, reinforcing steel is securely fixed and aligned in place. After a preliminary inspection of reinforcing steel cages of columns, formwork of this element starts. Since columns vary in size and shape within and amongst projects, and unless otherwise contractually specified, on site assembled timber boards to the required size and shape are usually used in shuttering the columns. The logic behind using timber boards in columns is twofold. On the one hand, is to minimise, as much as possible, the waste in plywood sheets, and the flexibility experienced in adjusting the size of columns between stories on the other. When the size of a column changes between two stories, rather than cutting and wasting expensive plywood sheets to adjust the size, sides of columns made of assembled timber boards are easily adjusted by simply striking one or more of the boards and reassembling them to the required dimension. As a result, minimum damage to timber boards, if any, is experienced in this process, and these boards can be reused in the same or different project. Following the final inspection of reinforcing steel cages and the alignments of columns, the sides of columns are erected, plumbed, securely tied and braced. After the inspection of formwork, concreting is ready to start.

Following curing of columns and walls, floor beams and/or slabs activities are ready to proceed. The first step in this activity is to set-out beam and/or slab soffit levels. The specified soffit levels are clearly marked on all vertical supporting members prior to the installation of falsework. When the levels have been inspected and verified, falsework starts to support the formwork of this activity. When the formwork is ready to start, a supporting frame of bearers and joists for beam and/or slab soffits is first erected. Again, and for the same reasons explained previously, timber boards, unless otherwise contractually specified, are used to make beam soffits and sides. Upon the re-inspection of the reduced level of soffits, beam sides are then placed in position and nailed. Finally, plywood panels are placed and nailed onto beam sides to create the forming surface of the slab panels.

When formwork is near completion, the reinforcing steel gang should be ready to start the fixing activity. Reinforcing steel bars of beams are fixed first followed by fixing the reinforcement of slab panels. It is important to note that fixing reinforcing steel bars of slab panels can not proceed unless the reinforcement of beams are already fixed and securely tied in place. The reason for this is simply because it would be impossible to place the reinforcement of beams in formwork moulds if the reinforcing bars of slabs were crossing the upper surface of beam moulds. Once the reinforcement of beams is fixed and securely tied in place, slab reinforcements can easily cross the beams between the stirrups.

Concreting of the floor would then proceed after the final inspection of falsework, formwork, reinforcing steel and other disciplines such as mechanical and electrical services. After curing the concreted floor, columns and walls supporting the following floor are ready to start and the cycle is repeated until the roof level.

4.5 Methods of Sites Observation

In order to effectively investigate the influence of buildability factors on the labour productivity of *in situ* reinforced concrete construction, several projects employing different design schemes will be observed. On the one hand, large amount of data had to be collected to ensure the results are robust, valid, reliable and statistically significant, and projects had to be carefully selected, as was previously explained, to quantify the influence of these factors on labour productivity with minimum interference from other variables on the other.

Due to the unique characteristics of each construction project, and the fact that numerous variables other than buildability influence the labour productivity on sites, it is important to minimise, as far as possible, the interference and effect of such variables. So only projects having common characteristics such as procurement and construction methods, site management level, type and geographical location were selected for observation. Unfortunately, projects having such common characteristics usually, share common design schemes too. As a result, the variability in labour productivity amongst such projects could be mainly due to either the variability in the skill of the operatives, the effectiveness of site management, or a combination of both. The skill of operatives varies amongst different gangs and unless the same gang is observed in different projects, it would be extremely difficult, if not impossible, to control this variable. However, as a general rule in research studies, the focus would be on comparing the average values obtained of the investigated subject. Therefore, maximising the number of productivity data points of a certain activity for instance, will minimise the influence of this variable. Furthermore, selecting projects employing different design schemes, yet sharing common characteristics, as practically as possible, will further reduce the effect of variables, other than buildability, on labour productivity. Thus, all projects selected for observation shared the common characteristics of contract procurement and construction methods, geographical location, and to a large extent, type and site management level.

The initial intention in this research project was to collect productivity data of the different activities within the main trades; formwork, reinforcing steel fixing, concreting and finishing at the macro-level. The reason for selecting this approach was due to its simplicity and practicality on the one hand, and the feasibility of monitoring several construction sites simultaneously on the other. In order to collect sufficient data, several sites were to be monitored simultaneously. Therefore, as we have previously indicated, the intermittent observation technique was selected as the data collection method in this research.

Activities and elements monitored within the formwork and reinforcing steel trades were foundations, ground beams, ground slabs, columns, walls and suspended floors. Suspended floors comprised either slab or beam-slab construction type. Pumped and skipped concrete of horizontal and vertical elements were also monitored, and when the specified floor finish was of the trowelled type, the finishing activity was monitored separately.

Once a project was selected for observation, the site management was approached by the observer and the objectives of the research project were explained. As soon as the permission to monitor and collect data was granted, an arrangement was made with the site management to provide the observer with copies of the necessary structural drawings of the project. The observer started the exercise by meeting with the field supervisors of the relevant trades. The observer introduced himself to the supervisors who were previously informed of the nature of the research by the site management, and the purpose of the data collection was explained. Every effort was made to stress the fact that the observer is unrelated to any management functions or interest, and that all the collected data was a confidential record and would be used for the sole purpose of the academic research project. Following this step, the observer presented the data collection forms and explained the procedure to be followed by site supervisors and/or gang members when filling them out.

In an attempt to verify the adequacy of the selected data collection technique, a ten-week pilot test was first conducted on the observed sites. During the first four weeks of the pilot test, the observer monitored the sites on a full-time basis to ensure that forms were filled out regularly, to answer any question that might arise regarding the data collection procedure, and to get himself acquainted with the mechanism and procedures at the activity level of formwork, reinforcing steel fixing, concreting and finishing trades. Each day at the jobsites was almost similar during the pilot test period. The observer would arrive on site, note the progress of the trade under observation, e.g. formwork or reinforcing steel fixing, check that inputs and delays of the previous workday had been recorded on the appropriate form and then cross-check the recorded information with a different gang member for verification. Once the observer had verified the recorded information, he would tour the site area and closely observe the mechanism of the trade for a period ranging from 45 to 60 minutes. Then the observer would thank the field personnel for their cooperation and move to a different construction site under observation where the same procedure was followed.

It should be noted however, that in order to maintain the confidence and cooperation of the field supervisors, and to minimise the "Hawthorne effect" [26] amongst labours during the presence of the observer on site, every effort was made by the observer to constantly reassure them that all data would remain confidential and would be used for the sole purpose of the academic research project. Gradually and over time, a comfortable and smooth relationship was developed between the observer and field personnel in almost all monitored projects, which enabled the observer to acquire the macro-level data required during the pilot test with minimum difficulties.

Once the adequacy of the selected data collection method had been verified, the observer gradually reduced the frequency of sites visits, and the productivity data recorded by site personnel for formwork, reinforcing steel, concreting and finishing trades were collected twice a week and when activities were completed. However, this routine was supported by occasional, but frequent "spot" visits, so that the observer could get an independent record of the site environment as well as the progress of activities. Another purpose of these visits was to indirectly reemphasise to the site personnel the importance of this research project to the observer.

The first phase of sites observation involved collecting productivity data at the macro-level. Data were collected for formwork, reinforcing steel fixing, concreting and finishing trades for a total period of six months from thirteen different construction sites. However, it was concluded that collecting data only at this level might not provide the required robustness, reliability and statistical significance of the results due to the limited number of data points which could be collected at the macro-level. As a result, it was decided to collect data at the micro-level too.

To illustrate the logic behind initiating the micro-level observation phase, it is best to provide a hypothetical example. If we are concerned with the reinforcing steel fixing activity in floor beams for instance, monitoring this activity at the macro-level involves collecting the total productive input applied in fixing the reinforcement of all beams in the floor regardless of the number of beams. When this activity is complete, a single productivity data point, quantified by the ratio of the total quantity of reinforcement fixed in all floor beams to the associated total productive input used to complete the activity, is obtained. Such macro-level activities may span for several days. For the same example, if we collect productivity data at the micro-level, we can maximise the amount of data points by observing pre-selected single beams in each floor. If we select, for instance, four beams in the observed floor, and monitor the productive input for each, we would be able to collect four productivity data points, i.e. one for each beam. This approach is equally applicable in most activities within the single trade.

In contrast to macro-level observation of an activity, which usually spans for several days and yields only one productivity data point, micro-level observation allows the observer to collect on a daily basis several productivity data points within an activity. Another advantage of the micro-level observation is that the effect of other variables, such as, project type, cost, size, procurement method, geographical location and site management level, on labour productivity is minimised at this level.

It is important to note that when the decision to initiate the micro-level observation phase was taken, the micro-level observation was planned to be conducted in parallel with the macro-level observation, and the results would be cross-checked to detect any deviation in findings between the two levels of observation.

However, by introducing the micro-level observation to the research project, the observer was confronted by a new challenge and difficulty. At that stage, the only feasible data collection technique to conduct a micro-level observation on individual elements within an activity was the continuous observation. Since several sites would be under observation simultaneously, the researcher had to make the choice between focusing on only few sites, a maximum of two or three, or try to get the full cooperation of labours at the micro-level of the activity. The researcher chose to pursue the later approach. The logic behind this decision was that, if the observer can get the cooperation of gang members involved with the activity at the micro-level, i.e. carpenters and steel fixers, to record, as accurately as possible, their individual inputs when, for instance, shuttering a single column or fixing the reinforcement in a single beam, then a maximum number of different sites could be monitored and substantial amount of productivity data points would be collected. Furthermore, this would enable the observer to use part of his time to analyse the physical outputs of the elements monitored.

In order to test the viability of this approach, an additional pilot test had to be conducted. Unlike the initial pilot test which was running simultaneously in all projects under observation for a period of ten weeks, the researcher decided to conduct a one-week test on only one project. This period was deemed adequate to find out whether or not this approach would be successful. The gang members of the relevant trades were approached and the observer explained his requirements and directly asked if they would be willing to cooperate? Although the answer was positive, they all made it clear to the observer that if this exercise would interfere with their work pace, they would not be able to provide any help. The observer explained what exactly was needed from them. They were asked to record the starting and finishing time of the micro-level activity, indicate the element mark the same way it is indicated on the drawings, and should the activity stop for any reason, record the time of the delay. The observer would then be able to estimate the productive input of the micro-level activity by simply subtracting the finishing time from the starting time, and subtracting any delay from the total input.

The pilot test was conducted for one week as previously indicated. During which time, the observer was continuously on site to supervise the exercise and to monitor the mechanism of the activity at the micro-level. The point of concern to the observer was the ability of gang members to accurately and consistently record the input of the monitored elements at this level. At the end of the pilot test period, the outcome of the exercise was successful and the same procedure was followed in the different sites monitored. In all observed projects, the intensity of the micro-level observation was gradually increased overtime, and the observer was able to collect in a single working day as many data points as he used to collect in three or four days. In order to keep a practical cooperation level however, the total number of elements selected for this type of observation in any monitored activity was kept to a minimum. It is also worth noting, that the cooperation amongst the gang members varied in different projects. Some members were not as cooperative as others and a few were not cooperative at all. When the observer was faced with this situation, micro-level inputs were collected only from cooperating gang members.

The major disadvantage of this technique however, is that when only one gang member performs the activity, the recorded input cannot be cross-checked and verified with a different member. Consequently, the accuracy of the collected input depends entirely on the accuracy provided by the gang member. In an attempt to verify the accuracy of such data, inputs of similar activities, i.e. similar elements having approximately the same physical outputs, collected from different observed sites were compared to spot-check major deviations. Micro-level raw data of single elements recorded during the previous workday were collected either daily or every other day form sites under observation.

The site observation phase of this research project extended over a total period of nineteen months. During which period, data were collected from thirty-nine different main sites. Macro-level productivity data were collected from all observed sites whereas the micro-level productivity data were collected from twenty-six different main sites, plus several other sites from which certain activities and elements were monitored.

It must be stated however, that had it not been for the fullest cooperation of gang members and field supervisors of the observed trades, collecting the required amount of productivity data for the various activities and trades, especially at the micro-level, would not have been possible.

4.6 Screening of Data

As was previously indicated, the observed activities were isolated foundations; raft foundations; ground beams; ground slabs; columns and walls; and suspended floors. The productivity data for such activities were screened for possible measurement errors or outliers. An outlier is defined as an unusual observation which lies outside the range of the data values [97]. Normal probability plots of the observed productivity data revealed that the values belong to almost normally distributed populations. A sample plot of micro-level steel fixing labour productivity of beams is shown in figure 4.5.

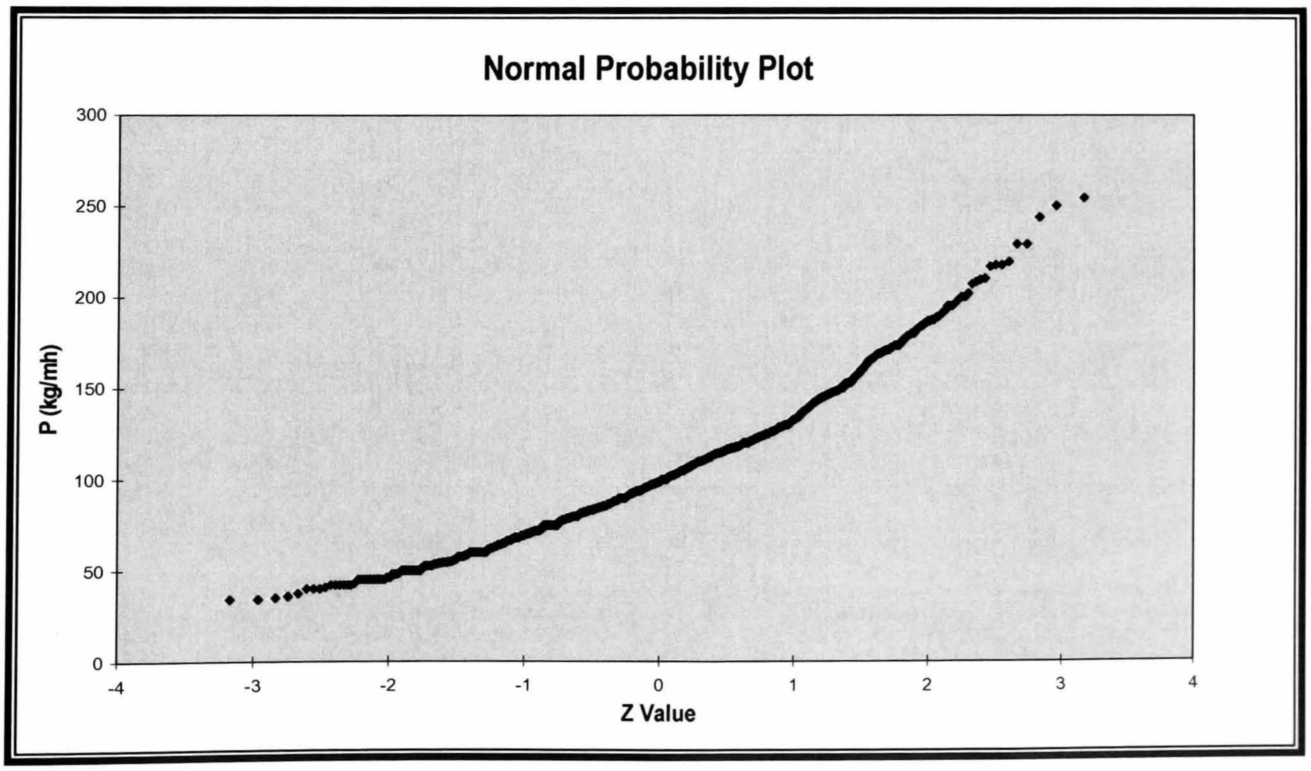


Figure 4.5 Normal Probability Plot – Micro-Level Reinforcing Steel Fixing Labour Productivity of Beams

As a statistical principle, almost all normally distributed data should lie within plus or minus three standard deviations from the mean [97]. Once an outlier is detected, and before the decision to discard it from the analysis is made, background information, which might explain the reason of its large deviation should be checked.

Outliers are often attributable to one of several causes. First, measurement error, second, misclassified measurement, i.e. measurement belongs to a different population, and finally, the measurement represents a rare event, i.e. the measurement is recorded correctly and belongs to the same population as the rest of the values, but represents a rare event or unusual performance [97].

It would be tempting to just discard such values from the analysis. However, before deciding their fate, the reasons behind the phenomena were investigated. The first step was to verify the measurements and make sure that the partitioned data within the models belonged to the appropriate populations. Having determined this, and following further investigation, the researcher found a common feature amongst all detected outliers; they were consistently associated with buildability factors which were much larger than their average values. To make this point clear, we will present some outlier productivity values detected in formwork, reinforcing steel and concreting trades, and illustrate the depicted pattern in context with other factors.

Formwork productivity data points of rectangular slab panels were collected at the micro-level. The average area of the observed slab panels was 25 m^2. All the outliers detected in this activity were associated with panels larger than 130 m^2 in areas. On the other hand, Reinforcing steel fixing productivity data points of isolated foundations had an average reinforcing steel diameter value of 16 mm, and 170 kg of reinforcement in quantity. Again, all outliers detected in this activity were associated with 25 mm reinforcing bar diameters, and total quantity of reinforcement larger than 600 kg. This pattern was also obvious in concreting. Pumped concrete trade had an average concrete volume of 89 m^3 per pour, and all outlier productivity values were detected in activities involved placing more than 400 m^3 of concrete. Based on the previous discussion, it was concluded that such values, although statistically qualified to be denoted as outliers, indeed were not, and none was removed from the analysis.

Once the physical output of an observed element had been analysed, its associated screened input was entered directly in the corresponding spreadsheet file according to the observed activity to transform the record into a meaningful productivity index. A sample analysis file is presented in Appendix J.

4.7 Coding System

Each project observed was given a unique set of numbers. The main purpose for this code was to identify the observed project in the analysis phase of this research. The code starts with the year number rounded to the last two digits, followed by the assigned number of the project. For example, if a certain project bears the number 0205, we can conclude that this project was observed in the year 2002 and was given the number 5. That way, we can automatically determine the year in which the project was monitored and its number. Following the same principle, if a project has the number 0326, we would then conclude that this project was observed in the year 2003 and was given the number 26.

In order to distinguish between the main monitored projects and other sites in which observations were limited to pre-selected activities or elements, a notation was added to the reference code. All sites in which only certain activities or elements were selected for observation, were assigned the unified number 0327, however, followed by a sequential site number, e.g. 0327-1, 0327-2, 0327-3, etc. Multi-storey buildings selected only for learning curve investigation were assigned the unified number 0328, and similarly followed by a sequential site number as shown above. The logic of this approach was for the researcher to easily identify the scope of work observed and partition the collected inputs of monitored activities within the project accordingly.

At the micro-level observation of elements, the element mark as originally identified on drawings was used. For example, F-10 denotes the isolated footing marked F-10 in the schedule of footings, C-7 denotes the column marked C-7 in the schedule of columns, and B-4 denotes the beam marked B-4 in the schedule of beams, etc.

4.8 Summary

Thirty-nine different main sites were monitored for a total period of nineteen months. Productivity data for the main trades of *in situ* reinforced concrete construction were collected at both micro and macro-levels using specifically designed forms. Macro-level productivity data were collected from all monitored sites whereas micro-level productivity data were collected from twenty-six different main sites for a total period of thirteen months. Apart from the main observed sites, and in an effort to complement the required productivity data, pre-selected activities and elements were also observed on other sites.

Since several sites were monitored simultaneously, the intermittent observation technique was selected to form the basis for the observation method. The cooperation of gang members on the monitored sites allowed the observer to collect a substantial amount of micro-level productivity data with minimum difficulties. Gang members involved with activities at the micro-level of the observed trades recorded the starting and finishing time of the activity in addition to any delays encountered in the process. This technique allowed the observer to quantify the productive input of the activity at the micro-level without having to continuously be present on sites and allowed him to use his time efficiently to quantify the physical outputs of the various elements monitored.

Macro-level productivity data were collected twice a week and when the activity was completed. On the other hand, micro-level productivity data were collected either daily or every other day. The accuracy and volume of the collected data has a direct impact on the robustness, reliability and validity of the derived relationships between labour productivity and the relevant buildability factors of the observed trades. Therefore, systematic, consistent and stringent data collection procedures were applied and followed on all sites monitored.

Chapter Five

Data Analysis Methodology

5.1 Introduction

The objective of this chapter is to illustrate the methodology employed in analysing the productivity data. Statistical methods and techniques are reviewed, and the various regression models developed for the relevant activities within the trades monitored are presented.

5.2 Statistical Methods

Productivity is a function of several factors, one of which is buildability [53]. One of the main objectives of this research is to investigate and quantify the influence of buildability factors on the labour productivity of *in situ* reinforced concrete trades.

In an observed activity within a monitored trade, several relevant buildability factors impact the labour productivity simultaneously. The net effect on labour productivity would be the total sum of the partial effects of all relevant factors. In view of this, an appropriate analysis devise must be used to determine the effect and relative influence of each variable on labour productivity. The ordinary least squares method, commonly referred to as linear regression, was selected to form the basis for the statistical analysis in this research project.

At the most basic level, the ordinary least squares method creates a linear model which produces the minimum average prediction error, and therefore, provides the best fit to the data points [5,97]. There are two reasons to conduct linear regression analysis. First, is to predict the value of a dependent variable if the value of the independent variable is known and second, to measure relationships between a dependent variable and one or more independent variables. In this research, the dependent variable is the observed labour productivity, and the independent variables are the buildability factors hypothesised to influence the labour productivity.

When there is only one independent variable, the model is determined through simple linear regression. If on the other hand there are two or more independent variables, the model is termed multiple linear regression. The general form of the regression model is as shown below [97]:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots + \beta_k X_k + \varepsilon \qquad \ldots 5.1$$

Where Y = the dependent variable; β_0 = intercept; β_i are the regression coefficients, where i = 1, 2,..., k; and ε = error or residual term.

The prediction equation of the model is expressed as follows:

$$\hat{Y} = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + \ldots + b_k X_k \qquad \ldots 5.2$$

Where $\hat{Y}$ = the predicted value of Y, also referred to as Y hat; b_0 = the value of $\hat{Y}$ when all the X_i values are zero; and b_i = the regression coefficient or the measure of the average rate of change in $\hat{Y}$ per unit change in X_i, holding all other variables in the model constant.

For simplicity however, hereafter, $\hat{Y}$ denoting the predicted value of Y will be referred to as Y.

Regression equations such as that shown above, with no interaction terms between independent variables, are called "main effects" models [98,116,117].

5.2.1 Regression Model Assumptions

As with most statistical procedures, the validity of the inferences depends upon certain assumptions being satisfied. The basic assumptions about regression models are as follows [97]:

1. linearity;
2. mean error of zero;
3. homoscedasticity;

4. normality; and

5. independence of error

Linearity means that the relationship between the dependent variable and each of the independent variables is linear.

The regression method assumes that residuals have an average value of zero. A regression residual is defined as the difference between an observed $\boldsymbol{Y}$ value and its corresponding predicted $\hat{\boldsymbol{Y}}$ value. This assumption is checked by plotting the value of each residual versus the corresponding value of the independent variable. When the model contains several independent variables, a plot would be constructed for each of the independent variables. If plots show a random pattern of residuals, then the assumption is likely to be satisfied.

Homoscedasticity implies that the residuals are randomly dispersed throughout the range of the dependent variable, i.e. residuals have a constant error variance for all values of the independent variables. This assumption is verified by plotting the regression residuals against the predicted values, i.e. $(\boldsymbol{Y}-\hat{\boldsymbol{Y}})$ versus $\hat{\boldsymbol{Y}}$. If the residuals have a constant variance, then the plot would show a random pattern.

Normality refers to the distribution of the error represented by residuals. Residuals are assumed to be normally distributed for each set of values of the independent variables. A powerful technique for checking normality is the normal probability plot. If the data are normally distributed, a linear trend will result. According to the central limit theorem however, when the sample size is large enough, even if the residuals are not normally distributed, the sampling distribution of the regression coefficients will still be normal [97]. Therefore, the violation of this assumption usually has little impact on the validity of the results.

Independence of the error or the residuals means that the residual difference is independent for each independent variable, i.e. current values should not be correlated with previous values in a data series. This assumption is mainly of importance when dealing with time series data.

In addition to these basic assumptions, other assumptions about regression models are of some importance and should be satisfied before meaningful, reliable and valid results are concluded. The most important of which is the absence of perfect or high multicollinearity [31,57,58,59,67,97,101]. Multicollinearity mainly occurs in regression models when the independent variables are either linear functions of one another or highly correlated with one another. When multicollinearity exists amongst independent variables, the standard error of regression coefficients becomes inflated, thus undermining the reliability of the results [97].

It should be noted however that it is unlikely that the previous assumptions about linear regression models are ever satisfied completely in the practical application of the regression analysis. Violations are expected and accepted as long as they are not severe enough to undermine the reliability and validity of the results. The regression procedure is quite flexible and robust with regards to moderate deviations from its basic assumptions, and with proper specifications of models, inferences could still be drawn with reasonable accuracy [97].

5.2.2 Categorical-Variable Regression

Although linear regression method assumes that the independent variables included in the model are continuous, i.e. quantitative in nature, it is not uncommon to use categorical or qualitative independent variables. Some variables such as, column or slab geometry, layer location of reinforcement or the category of concrete workability, defy explicit quantifications and could be expressed only in a qualitative manner. One of the most common procedures to quantify such variables in linear regression is to introduce "indicator" or "dummy" variables [42,45,67,96,97]. The simplest case in introducing a dummy variable is when the qualitative variable has only two categories. For instance, if beams are either linear or curved, then to quantify the type of beam in the regression model, we would introduce a binary dummy variable and denote it for example, beam geometry, which assumes the values of either 0 or 1, e.g. 0 if beam is linear in span and 1 if curved. The coding however is arbitrary and it would be just as valid to code curved beams with 0 and linear beams with 1. When the qualitative variable has more than two categories, more than one dummy variable is required to represent the original variable. As a general rule, for qualitative variables with K categories, we introduce $K-1$ dummy variables [45,67,96].

The reason behind introducing one variable less than the number of categories is to avoid perfect multicollinearity amongst the dummy variables. If we introduce as many dummy variables as the number of categories, the regression model becomes over parameterised and the effects of the intercept and the extra dummy variable inseparable.

Regardless of the number of categories however, the arbitrarily omitted dummy variable is called the "reference" or "base" category, and the other dummy coefficients are interpreted in terms of the expected average change relative to it.

A multiple regression model may include continuous variables, dummy variables or a combination of both. A typical multiple regression model involves both types of variables is shown below:

$$Y = b_0 + b_1 X_1 + b_2 D_2 \qquad \text{...5.3}$$

Where X_1 = continuous variable; and D_2 = dummy variable.

The coefficient of the dummy variable b_2 is interpreted as the average difference in the dependent variable Y, between the category coded 1 and the category coded 0 of the dummy variable D_2, holding the continuous variable constant. When there is no interaction between the dummy and the continuous variables in the regression model, the dummy variable is called an "intercept dummy variable", i.e. there are parallel slopes for the two categories, but different intercepts [42,67].

5.2.3 Interaction-Regression Models

So far, we have introduced the "main effects" models. Such models assume no interaction between the independent variables and therefore the unique effect of each independent variable on the dependent variable is quantified whilst all other independent variables in the model are held constant. However, there are many cases when the effect of an independent variable on the dependent variable depends on the level or intensity of another independent variable in the model [3,36,42,57,58,59,67]. When such a situation is encountered, an interaction term between the two independent variables is added to the model to incorporate their joint effect on the dependent variable over and above their separate effects. An interaction term is added to the model as a cross product of the interacting independent variables. A typical regression model involving interaction between continuous and dummy variables has the following basic form [57,58,59,67]:

$$Y = b_0 + b_1 X_1 + b_2 D_2 + b_3 (X_1 * D_2) \qquad ...5.4$$

Where X_1 = continuous variable; D_2 = dummy variable; and $(X_1 * D_2)$ = interaction term between X_1 and D_2. The interaction coefficient b_3, quantifies the average difference in the slope of the relationship between the continuous independent variable X_1 and the dependent variable Y for the two categories represented by the dummy variable D_2. It should be noted that although we have shown the most commonly encountered interaction case in this model, i.e. interaction between continuous and dummy variables, interaction can occur between two continuous or two dummy variables. Moreover, a multiple regression model may involve several interaction terms.

In contrast to the "intercept dummy variable", which changes the intercept but not the slope when a particular condition of the dummy variable is met, when a dummy variable interacts with a continuous variable, the slope of the relationship between the dependent variable and the independent variable would be different depending on whether the condition specified by the dummy variable is met. When dummy and continuous variables interact, the dummy variable is referred to as the "slope dummy variable" [42,67].

5.2.4 Statistical Significance Tests

As with most statistical procedures, the reliability of regression relationships is determined by conducting significance tests. By definition, statistical significance represents the probability that a relationship found in the data is attributable to chance or random errors [97]. The chance of concluding that there is a relationship when indeed there is not is referred to a type I error. Typically, researchers tend to minimise such type of error by controlling the probability of its occurrence.

The probability of making a type I error is called the "level of significance" and denoted by the symbol α [97]. The lower the significance level, the lower the probability of asserting a non-existent relationship, therefore, the higher the reliability of the conclusion. However, selecting a stringent significance level increases the probability of making a type II error; concluding that there is no relationship when in fact there is, thus undermining the power of the test. Nevertheless, greater care should be directed towards avoiding the type I error based on the seriousness of falsely asserting a relationship compared with failing to conclude that a relationship exists.

In most research, and depending on the research importance and objectives, the selected significance level ranges from 0.010 to 0.10. Based on several previous productivity research [17,25,50,65,74,79,103,114,115], as was previously indicated in chapter one, a significance level of 0.050 was selected as an acceptable measure of the reliability of inferences, and was used throughout this research project.

The statistical significance in regression models is measured by the following parameters [31,67,96,97]:

1. Correlation Coefficient, R
2. Coefficient of Determination, R^2
3. Standard Error, SE
4. Degrees of Freedom, DF

5. F-ratio

6. t-statistic

7. p-value

8. Variance Inflation Factor, VIF

The correlation coefficient, measures the strength of linear correlation between the dependent and independent variables in the regression model. The coefficient of determination indicates the percent of variance in the dependent variable which can be explained by the independent variables of the model. Both, the coefficients of correlation and determination are tests of goodness of fit, which determines how well the linear regression model is related to the data. The higher the coefficients of correlation and determination in the regression model, the better the goodness of fit.

In general, the standard error is a measure of the sampling error. In regression analysis, we have two estimates of standard error; the standard error of the regression model, and the standard error of the estimated coefficients. The standard error of the overall model represents the estimated standard deviation of the residuals whereas the standard error of the regression coefficients represents the variability we would expect to see if a different sample is used to estimate the coefficients. Typically, the smaller the standard error, the better the sample statistic estimates of the population parameter.

Degrees of freedom basically represent the number of sample values that are free to vary [97], i.e. the number of observations minus the number of necessary relations amongst these observations. In other words, the degree of freedom tells us the number of useful data available for estimation. This concept is important in regression analysis. For instance, if we have two data points, we can always join them by a straight regression line and get a perfect correlation. Hence, the lower the degree of freedom is, the poorer the estimation is.

The F-ratio is a test statistic utilised to assess the overall adequacy of the regression model. The F-ratio depends on its degrees of freedom, which in turn depends on the sample size. Two degrees of freedom are associated with the F-ratio; the numerator and denominator degrees of freedom. In regression analysis, the numerator degrees of freedom are associated with the regression and equal the number of regressors used, and the denominator degrees of freedom with the residual or error. Throughout the analysis part of this research, the F-value will be reported together with its degrees of freedom explicitly in parentheses form, e.g. F(regression degrees of freedom, residual degrees of freedom). The magnitude of the F-ratio determines whether any of the estimated regression coefficients is significantly different from zero. An F-ratio greater than 1 indicates that at least one regression coefficient in the model is significantly different from zero and that the overall regression model is useful for predicting the dependent variable.

The t-statistic is a test statistic used to assess the statistical significance of the estimated coefficients of the regression model. It is computed from the information provided by the sample, i.e. average, standard deviation and sample size, to provide a measure of its departure from the null hypothesis value of the parameter, i.e. that the regression coefficient is insignificantly different from zero [97]. Based on the pre-selected significance level α, the rejection regions for the test can be determined. The value at the boundary of the rejection region is called the "critical value", and any computed t-statistic value which is greater in absolute value than the critical value falls into the rejection region; therefore, the null hypothesis of the parameter is rejected, i.e. we conclude that the regression coefficient is significantly different from zero. Thus, no matter how large or small the computed t-statistic is, the decision regarding the null hypothesis is clear cut. The null hypothesis is rejected, i.e. we conclude that the regression coefficient is significantly different from zero, if the computed t-statistic falls into the rejection region, and the null hypothesis is not rejected, i.e. we conclude that the regression coefficient is insignificantly different from zero, if the computed t-statistic falls outside the rejection region [97].

Based on the aforementioned discussion, a question arises: if the value of the t-statistic falls into the rejection region, then how do we measure the extent to which the data disagree with the null hypothesis? In other words, how do we measure the degree of significance of the test results? This is answered by looking at the p-value. The p-value represents the probability of computing a t-statistic value equal to or greater than (in absolute value) the actual computed t-statistic, if the null hypothesis is true. Therefore, the smaller the p-value, the greater the extent of disagreement between the data and the null hypothesis, and the more significant the result. In general, if the p-value is less than the significance level α, we reject the null hypothesis [97].

The variance inflation factor, VIF, is used in regression analysis to assess the multicollinearity amongst the independent variables in the model. When the independent variables are highly correlated with one another, as we have previously indicated, the standard error of the regression coefficients becomes inflated, thus undermining the reliability of the estimates. Although there is no agreement on a formal cut-off value to be used with VIF, values of VIF exceeding 10 are often regarded as indicating multicollinearity [6,49]. Since strongly correlated independent variables are redundant, an effective procedure to minimise multicollinearity in regression is to drop the strongly correlated independent variables form the model [97].

5.2.5 Standardised Regression Coefficients

In addition to quantifying and assessing the statistical significance of the regression coefficients, it is also important to investigate the relative importance and influence of the independent variables on the dependent variable. A multiple regression model may involve several independent variables having different units of measurement. Consequently, direct comparison of the size of various coefficients in order to assess their relative influence on the dependent variable could be spurious.

Before a meaningful investigation of the relative influence of the independent variables can be conducted, the regression coefficients of the independent variables in the model have to be standardised [58,62,67]. The standardised regression coefficients are then measured on the same scale, with a mean of zero and a standard deviation of one, and therefore are directly comparable to one another with the largest coefficient in absolute value indicating the greatest influence on the dependent variable.

A regression coefficient is standardised using the following formula:

$$b_k^* = b_k\left(\frac{s_k}{s_y}\right) \qquad \ldots 5.5$$

Where b_k^* = standardised regression coefficient of the k^{th} independent variable; b_k = regression coefficient of the k^{th} independent variable; s_k = standard deviation of the k^{th} independent variable; and s_y = standard deviation of the dependent variable. Commonly, standardised regression coefficients are referred to as beta weights.

In this research, predictive regression models for the monitored activities within the relevant trades were developed using the labour productivity as the dependent variable. Relevant buildability factors hypothesised to have an influence on the labour productivity were used as independent variables. When encountered, qualitative variables were quantified using indicator or dummy variables to represent their categories in the models. All regression analyses were conducted using the *PHStat* software, a statistics add-in for Microsoft® Excel. The first step after quantifying the parameters of the regression models was to verify that there was no gross violation to any of the previously explained basic assumptions of the regression method. Then, statistical tests were examined to determine the overall usefulness of the predictive models, and to assess the significance of the results. The final step before reporting the results was to quantify the standardised regression coefficients of the independent design variables in order to determine their relative influence on the dependent variable; the labour productivity.

5.3 Investigation of Learning Curve Theory

As we have previously indicated in chapter three, the unit straight-line learning curve model was selected to form the basis for investigating the applicability of learning curve theory to recurring activities of reinforced concrete trades; formwork, reinforcing steel and pumped concrete.

The straight-line unit model is expressed as a power function in the following form [110,111]:

$$Y = T * X^b \qquad \text{...5.6}$$

Where Y = unit man-hours to produce the X^{th} unit; T = man-hours of the 1st production unit; X = Floor or cycle number; and b = slope of the logarithmic curve, which is calculated as follows:

$$b = \frac{Ln S}{Ln 2} \qquad \text{...5.7}$$

Where S = learning rate and is defined as the percentage reduction in the unit input, i.e. man-hours, which results from doubling the number of units completed.

Equation 5.7 can be re-written as:

$$S = (2^b) * 100 \qquad \text{...5.8}$$

Taking the natural logarithm of both sides of the straight-line unit model equation, and using the fact that:

$$Ln X^b = b * Ln X$$

the straight-line unit model equation can be re-written as:

$$Ln Y = Ln T + b * Ln X \text{ or more commonly;} \qquad \text{...5.9}$$

$$y = t + b * x$$

It should be noted however, that unless special learning curve software is employed, data used in standard spreadsheet analysis must be transformed logarithmically in order to present the learning curve equation in standard power function format using equation 5.7, and the following equation:

$$T = e^t \qquad \text{...5.10}$$

Where t is the intercept given by the standard linear equation, and e is the natural logarithm base ≅ 2.7183.

The relationship between the productive input and its associated cycle number of recurring activities was investigated using simple linear regression technique. In an observed project, the dependent variable is the total productive input used to complete the activity of the monitored independent cycle. Upon the conclusion of the recurring activities, the data were transformed into logarithmic values and the dependent variable, i.e. man-hours, was plotted against the independent variable; the cycle or floor number. As was previously indicated in chapter three, since the data were transformed into logarithmic values, a straight line plot should result.

If learning has an impact on labour productivity, then we would expect a reduction in labour input as the cycle number increases. The t-statistic test was used to assess the significance of the estimated slope coefficient of the linear regression equation. The learning rate of each observed recurring activity was quantified, and the unit straight-line model equations in the standard linear and power function formats were determined for each observed project.

This procedure was repeated for each project and the applicability of learning curve theory to each trade involved in reinforced concrete recurring activities was determined.

5.4 Regression Models

This section presents the regression models for the trades of formwork, reinforcing steel, concreting and power-trowelling. Buildability factors hypothesised to influence the labour productivity at both observed levels macro and micro are also presented. Binary variables are highlighted, and when the effect of an independent variable on the dependent variable was hypothesised to be influenced by the level or intensity of another independent variable in the model, an interaction term between the two independent variables is included as a cross product of their parameters. It should be noted that within a single regression model, several possible interaction terms may be hypothesised and tested. In order to obtain reliable estimates however, only statistically significant terms having reasonable variance inflation factors, i.e. VIF $\leq$ 10, were included in the regression equations. Significant interaction terms are expressed in the relevant presented regression models. For all models, the dependent variable is labour productivity.

5.4.1 Formwork

Table 5.1 Predictive Regression Model for Axes Setting-out Activity of Isolated Foundations

Macro-Level Observation
Buildability Factor
Grid Pattern, ALO
Regression Model
$P(\text{No. of footings / mh}) = b_0 + b_1\, ALO$

Table 5.2 Predictive Regression Models for Formwork Productivity of Isolated Foundations

Macro-Level Observation
Buildability Factors
Grid Pattern, ALO
Variability of footing sizes, VOF
Total shutter area of footings (m^2), TSA
Average shutter area of footings (m^2), ASA
Regression Model
$P(m^2 / mh) = b_0 + b_1\, ALO + b_2\, VOF + b_3\, TSA + b_4\, ASA$
Micro-Level Observation
Buildability Factor
Shutter area of the observed footing (m^2), SA
Regression Model
$P(m^2 / mh) = b_0 + b_1\, SA$

Table 5.3 Predictive Regression Model for Formwork Productivity of Base Slabs

Macro-Level Observation
Buildability Factors
Total shutter area of edge forms (m^2), TSA
Geometric factor, GF
Regression Model
$P(m^2 / mh) = b_0 + b_1\, TSA + b_2\, GF$

Table 5.4 Predictive Regression Models for Formwork Productivity of Ground Beams

Macro-Level Observation
Buildability Factors
Variability of beam sizes, VOB
Total shutter area of beams (m^2), TSA
Total Number of beam intersections, TNJ
Regression Model
$P(m^2 / mh) = b_0 + b_1\, VOB + b_2\, TSA + b_3\, TNJ$
Micro-Level Observation
Buildability Factors
Shutter area of the observed beam (m^2), SA
Number of intersections in the observed beam, NJ
Regression Model
$P(m^2 / mh) = b_0 + b_1\, SA + b_2\, NJ$

Table 5.5 Predictive Regression Model for Axes Setting-out Activity of Columns

Macro-Level Observation
Buildability Factor
Grid Pattern, ALO
Regression Model
$P(No.\ of\ Columns / mh) = b_0 + b_1\, ALO$

Table 5.6 Predictive Regression Models for Formwork Productivity of Columns

Macro-Level Observation
Buildability Factors
Grid Pattern, ALO
Variability of column sizes, VOC
Repetition factor, RF[1]
Total shutter area of columns (m^2), TSA
Average shutter area of columns (m^2), ASA
Percentage of circular columns, PCC
Regression Model
$P(m^2/mh) = b_0 + b_1\,ALO + b_2\,VOC + b_3\,RF + b_4\,TSA + b_5\,ASA + b_6\,PCC$
Micro-Level Observation
Buildability Factors
Shutter area of the observed column (m^2), SA
Geometry of the observed column, CGeom[2]
Regression Model
$P(m^2/mh) = b_0 + b_1\,SA + b_2\,CGeom$

[1]Dummy variable indicating shutter repetition which has the following two values: 0 if column shutter is repeated, and 1 if 1st shutter.

[2]Dummy variable indicating column geometry which has the following two values: 0 if column is rectangular in shape, and 1 if circular.

Table 5.7 Predictive Regression Model for Formwork Productivity of Walls

Macro-Level Observation
Buildability Factors
Total shutter area (m^2), TSA
Geometric factor, GF
Regression Model
$P(m^2 / mh) = b_0 + b_1 TSA + b_2 GF$

Table 5.8 Predictive Regression Model for Formwork Productivity of Suspended Floors

Macro-Level Observation
Buildability Factors
Variability of beam sizes in floor, VOB
Repetition factor, RF[1]
Floor area (m^2), FA
Average slab panel area (m^2), APA
Total number of beam intersections in floor, TNJ
Beam-Floor ratio, BFR
Percentage of curved beams in floor, PCB
Percentage of non-rectangular slab panels in floor, PNRP
Regression Model
$P(m^2 / mh) = b_0 + b_1 VOB + b_2 RF + b_3 FA + b_4 APA + b_5 TNJ + b_6 BFR + b_7 PCB + b_8 PNRP$

[1]Dummy variable indicating shutter repetition which has the following two values: 0 if 1st shutter of floor, and 1 if floor shutter is repeated.

Table 5.9 Predictive Regression Model for Formwork Productivity of Suspended Beams

Micro-Level Observation
Buildability Factors
Repetition factor, RF[1]
Shutter area of the observed beam (m^2), SA
Number of intersections in the observed beam, NJ
Geometry of the observed beam span, GOS[2]
(GOS * SA)[3]
(GOS * NJ)[3]
(GOS * RF)[3]
Regression Model
$P(m^2/mh) = b_0 + b_1 RF + b_2 SA + b_3 NJ + b_4 GOS + b_5 (GOS * SA) + b_6 (GOS * NJ) + b_7 (GOS * RF)$

[1]Dummy variable indicating shutter repetition which has the following two values: 0 if 1st shutter of beam, and 1 if beam shutter is repeated.

[2]Dummy variable indicating span geometry which has the following two values: 0 if linear beam, and 1 if curved.

[3]Interaction terms.

Table 5.10 Predictive Regression Model for Formwork Productivity of Suspended Slab Panels

Micro-Level Observation
Buildability factors
Repetition factor, RF[1]
Area of the observed slab panel (m^2), A
Geometry of the observed slab panel, GOP[2]
(GOP * RF)[3]
Regression Model
$P(m^2 / mh) = b_0 + b_1 RF + b_2 A + b_3 GOP + b_4 (GOP * RF)$

[1]Dummy variable indicating shutter repetition which has the following two values: 0 if 1st shutter of panel, and 1 if panel shutter is repeated.

[2]Dummy variable indicating panel geometry which has the following two values: 0 if panel is rectangular in shape, and 1 if non-rectangular.

[3]Interaction term.

5.4.2 Reinforcing Steel

Table 5.11 Predictive Regression Models for Reinforcing Steel Fixing Productivity of Isolated Foundations

Macro-Level Observation
Buildability Factors
Variability of footing sizes, VOF
Characteristic bar diameter (mm), CBDia
Total quantity of reinforcement fixed (kg), TQ
Regression Model
$P(kg/mh) = b_0 + b_1\, VOF + b_2\, CBDia + b_3\, TQ$
Micro-Level Observation
Buildability Factors
Characteristic bar diameter fixed in the observed footing (mm), CBDia
Quantity of reinforcement fixed in the observed footing (kg), Q
Regression Model
$P(kg/mh) = b_0 + b_1\, CBDia + b_2\, Q$

Table 5.12 Predictive Regression Models for Reinforcing Steel Fixing Productivity of Base Slabs

Macro-Level Observation
Buildability Factors
Characteristic bar diameter (mm), CBDia
Total quantity of reinforcement fixed (kg), TQ
Geometry of slab, Geom[1]
(Geom * TQ)[2]
Regression Model
$P(kg/mh) = b_0 + b_1 \, CBDia + b_2 TQ + b_3 \, Geom + b_4 \, (Geom * TQ)$
Micro-Level Observation
Buildability Factors
Characteristic bar diameter fixed in the observed layer (mm), CBDia
Quantity of reinforcement fixed in the observed layer (kg), Q
Geometry of slab, Geom[1]
(Geom * Q)[2]
Layer location, LLoc[3]
Regression Model
$P(kg/mh) = b_0 + b_1 \, CBDia + b_2 Q + b_3 \, Geom + b_4 \, (Geom * Q) + b_5 \, LLoc$

[1]Dummy variable indicating slab geometry which has the following two values: 0 if slab is rectangular, and 1 if non-rectangular.

[2]Interaction term.

[3]Dummy variable indicating the layer location of reinforcement which has the following two values: 0 if bottom layer, and 1 if top.

Table 5.13 Predictive Regression Models for Reinforcing Steel Fixing Productivity of Columns

Macro-Level Observation
Buildability Factors
Variability of column sizes, VOC
Characteristic bar diameter (mm), CBDia
Total quantity of reinforcement fixed (kg), TQ
Percentage of reinforcement fixed in circular columns, PSCC
Regression Model
$P(kg/mh) = b_0 + b_1\,VOC + b_2\,CBDia + b_3\,TQ + b_4\,PSCC$
Micro-Level Observation
Buildability Factors
Characteristic bar diameter fixed in the observed column (mm), CBDia
Quantity of reinforcement fixed in the observed column (kg), Q
Geometry of the observed column, CGeom[1]
(CGeom * Q)[2]
Regression Model
$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,Q + b_3\,CGeom + b_4\,(CGeom * Q)$

[1]Dummy variable indicating column geometry which has the following two values: 0 if column is rectangular in shape, and 1 if circular.

[2]Interaction term.

Table 5.14 Predictive Regression Model for Reinforcing Steel Fixing Productivity of Walls

Macro-Level Observation
Buildability Factors
Characteristic bar diameter (mm), CBDia
Total quantity of reinforcement fixed (kg), TQ
Thickness of wall (mm), T
Regression Model
$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,TQ + b_3\,T$

Table 5.15 Predictive Regression Models for Reinforcing Steel Fixing Productivity of Beams

Macro-Level Observation
Buildability Factors
Variability of beam sizes, VOB
Characteristic bar diameter (mm), CBDia
Characteristic stirrup diameter (mm), CSDia
Total quantity of reinforcement fixed (kg), TQ
Average width of beams (mm), AW
Average depth of beams (mm), AD
Percentage of reinforcement fixed in curved beams, PRCB
Regression Model
$P\,(kg\,/\,mh) = b_0 + b_1\,VOB + b_2\,CBDia + b_3\,CSDia + b_4\,TQ + b_5\,AW + b_6\,AD + b_7\,PRCB$
Micro-Level Observation
Buildability Factors
Characteristic Bar diameter fixed in the observed beam (mm), CBDia
Stirrup diameter fixed in the observed beam (mm), SDia
Quantity of reinforcement fixed in the observed beam (kg), Q
Width of the observed beam (mm), W
Depth of the observed beam (mm), D
Geometry of the observed beam span, GOS[1]
(GOS ∗ D)[2]
Regression Model
$P\,(kg\,/\,mh) = b_0 + b_1\,CBDia + b_2\,SDia + b_3\,Q + b_4\,W + b_5\,D + b_6\,GOS + b_7\,(GOS * D)$

[1]Dummy variable indicating span geometry which has the following two values: 0 if linear beam, and 1 if curved.

[2]Interaction term.

Table 5.16 Predictive Regression Models for Reinforcing Steel Fixing Productivity of Slab Panels

Macro-level Observation
Buildability Factors
Average panel area (m^2), AVA
Characteristic bar diameter (mm), CBDia
Total quantity of reinforcement fixed (kg), TQ
Percentage of reinforcement fixed in non-rectangular slab panels, PSNP
Regression Model
$P(kg/mh) = b_0 + b_1\,AVA + b_2\,CBDia + b_3\,TQ + b_4\,PSNP$
Micro-Level Observation
Buildability Factors
Characteristic bar diameter fixed in the observed slab panel (mm), CBDia
Total quantity of reinforcement fixed (kg), TQ
Quantity of reinforcement fixed in the observed layer (kg), Q
Geometry of the observed slab panel, GOP[1]
(GOP * TQ)[2]
Layer location, LLoc[3]
Regression Models
$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,TQ + b_3\,GOP + b_4(GOP * TQ)$ $P(kg/mh) = b_0 + b_1\,CBDia + b_2\,Q + b_3\,GOP + b_4\,(GOP * Q) + b_5\,LLoc$

[1]Dummy variable indicating panel geometry which has the following two values: 0 if panel is rectangular in shape, and 1 if non-rectangular.

[2]Interaction term.

[3]Dummy variable indicating the layer location of reinforcement which has the following two values: 0 if bottom layer, and 1 if top.

5.4.3 Concreting and Trowelling

A. Concreting

Table 5.17 Predictive Regression Model for Pumped and Skipped Concrete

Buildability Factors
Volume of concrete placed (m^3), V
Height relative to ground level (m), H
Steel congestion ratio (Kg/m^3), SCR
Concrete workability (HWRK, LWRK)[1]
Regression Model
$P(m^3/mh)=b_0+b_1V+b_2H+b_3SCR+b_4HWRK+b_5LWRK$

[1]Dummy variables indicating concrete workability which has the following three categories: High, medium and low. The omitted medium workability was selected as the base category, and the other two categories presented in the model are compared relative to it. When the specified workability of the observed concreting activity is of the high category, the value of 1 would be substituted for the variable termed HWRK and the value of 0 for LWRK. These values would be switched if the concrete workability is of the low category, i.e. HWRK = 0, and LWRK = 1. When the concrete workability is of the medium category however, a zero value is substituted for both variables; HWRK and LWRK in the model.

B. Trowelling

Table 5.18 Predictive Regression Model for Trowelling Activity

Factors
Area of the trowelled floor (m^2), A
Number of trowelling machines used in the activity, NOM
Regression Model
$P(m^2/mh)=b_0+b_1A+b_2NOM$

5.5 Summary

The ordinary least squares method, commonly referred to as linear regression was selected to form the basis for the analysis phase of this research project. The basic assumptions of the regression procedure were presented and explained. The use of binary variables was illustrated and the procedure to quantify their effects using indicator or dummy variables was elaborated. Regression models with no interaction between or amongst the independent variables, as well as interaction regression were considered. The difference between the intercept and slope dummy variables was explained.

Relevant statistical significance tests were introduced and explained. Throughout the analysis phase of this research project, a significance level of 0.050 was used, i.e. there is 5% probability that the researcher would erroneously assert that a relationship exists.

The relative influence of buildability factors on labour productivity can be quantified by standardising the regression coefficients. The standardised coefficients, also referred to as beta weights, have a common measurement scale, with a mean of zero and a standard deviation of one, and are thus directly comparable to one another with the largest regression coefficient in absolute value indicating the greatest influence on the dependent variable.

The unit straight-line learning curve model equations can be presented in both formats; standard linear and power function. Learning curve theory will be applied to the activities of formwork, reinforcing steel fixing and pumped concrete.

Finally, regression models have been developed for all observed activities at both macro and micro-levels.

Chapter Six

Analysis of Formwork Productivity

6.1 Introduction

Buildability factors hypothesised to influence formwork labour productivity of the various monitored activities were introduced and discussed in chapter three. In addition, the ordinary least squares method utilised throughout the analysis phase of this research project was explained in chapter five. In this chapter, the impact and relative influence of buildability factors on formwork labour productivity of the relevant monitored activities and elements are presented and discussed.

6.2 Data Distribution & Characteristics of Observed Projects

Productivity data of the activities within the formwork trade were collected at the macro and micro-levels. As we have previously explained in chapter three, the macro-level observation method involves collecting the overall productive inputs, i.e. total productive man-hours used to complete the observed activity. On the other hand, the micro-level observation is characterised by collecting the productive inputs of selected single elements within the activity. The collected data at both observation levels for the various activities monitored were distributed as follows:

A. Macro-Level Observation

At the macro-level, a total of 957 productivity data points were collected and distributed as follows:

1. Isolated foundations, 49 data points
2. Raft foundations, 34 data points
3. Ground beams, 54 data points
4. Ground slabs and edge forms, 223 data points

5. Columns, 182 data points

6. Walls, 235 data points

7. Suspended floors, 180 data points

B. Micro-Level Observation

At the micro-level, a total of 2922 data points were collected, and were distributed as follows:

1. Isolated foundations, 207 data points

2. Ground beams, 334 data points

3. Rectangular columns, 471 data points

4. Circular columns, 265 data points

5. Linear beams, 653 data points

6. Curved beams, 175 data points

7. Rectangular slab panels, 473 data points

8. Non-rectangular slab panels, 344 data points

Productivity data used in this research to investigate the influence of buildability factors on labour productivity of formwork, reinforcing steel, concreting and finishing were collected from various projects. Such projects included residential and office buildings, commercial centres, industrial facilities and warehouses. Table 6.1 summarises the important characteristics of the main observed projects.

Table 6.1 Characteristics of Observed Projects

Project Number	Type	Total Floor Area (m^2)	Number of Stories	Contract Procurement Method	Observation Period
0201	Residential	3394	8	Lump Sum	April – September 2002
0202	Residential	828	3	Lump Sum	March – July 2002
0203	Residential	5232	9	Lump Sum	April – September 2002
0204	Residential	2996	7	Lump Sum	April – September 2002
0205	Residential	990	3	Lump Sum	March – July 2002
0206	Residential	869	3	Lump Sum	March – June 2002
0207	Residential	1138	3	Lump Sum	March – July 2002
0208	Residential	1449	3	Lump Sum	April – July 2002
0209	Residential	1214	3	Lump Sum	April – August 2002
0210	Residential	1302	3	Lump Sum	April – August 2002
0211	Sports Complex	N/A[1]	1	Lump Sum	June – July 2002
0212	Office Building	4400	11	Lump Sum	June 2002
0213	Residential	3568	6	Lump Sum	March – August 2002
0301	Residential	635	3	Lump Sum	January – May 2003
0302	Residential	5050	11	Lump Sum	January – August 2003
0303	Residential	558	2	Lump Sum	January – April 2003
0304	Office Building	1366	6	Lump Sum	March – July 2003
0305	Residential	4241	10	Lump Sum	January – August 2003
0306	Residential	1526	3	Lump Sum	April – August 2003
0307	Residential	584	2	Lump Sum	March – June 2003
0308	Warehouse	879	2	Lump Sum	May – June 2003
0309	Rest Area	351	1	Lump Sum	April – June 2003
0310	Warehouse	1234	2	Lump Sum	April – July 2003
0311	Industrial	242	1	Lump Sum	June – July 2003
0312	Industrial	1402	1	Lump Sum	August – November 2003
0313	Convention Hall	690	1	Lump Sum	June – August 2003
0314	Residential	1737	3	Lump Sum	May – August 2003
0315	Residential	815	3	Lump Sum	March – May 2003
0316	Residential	863	3	Lump Sum	August – November 2003
0317	Residential	728	3	Lump Sum	August – December 2003
0318	Residential	560	2	Lump Sum	October – December 2003
0319	Warehouse	1876	1	Lump Sum	April – July 2003
0320	Commercial Centre	10970	3	Lump Sum	April – January 2004
0321	Warehouse	2387	3	Lump Sum	May – November 2003

[1]Observation of this project was limited to foundations.

Table 6.1 Characteristics of Observed Projects (Cont'd)

Project Number	*Type*	*Total Floor Area (m^2)*	*Number of Stories*	*Contract Procurement Method*	*Observation Period*
0322	*Warehouse*	*1541*	*2*	*Lump Sum*	*June – September 2003*
0323	*Residential*	*1444*	*3*	*Lump Sum*	*August – December 2003*
0324	*Residential*	*3375*	*8*	*Lump Sum*	*June – December 2003*
0325	*Residential*	*966*	*3*	*Lump Sum*	*August – December 2003*
0326	*Residential*	*1417*	*6*	*Lump Sum*	*April – September 2003*

6.3 Gang Characteristics

A typical observed formwork gang comprises, on average, five to seven members. The gang is headed by a leader who is usually a foreman with field experience over twenty years. The foreman's main duties are to plan, direct, supervise and control work procedures on site. Gang members are formwork carpenters and assistants with field experience ranges from ten to twenty years and two to five years for carpenters and assistants respectively. Usually, gang members work in pairs, i.e. a carpenter and an assistant, although it is not unusual for an assistant to work with two and in extreme cases three carpenters at the same time. If however the task is small enough, e.g. forming a small size footing, beam or edge, the carpenter would be performing individually. In addition to the formwork trade, the gang is also responsible for the concreting trade. In other words, the gang would be subcontracted to undertake both; formwork as well as concreting trades. On all observed sites, formwork and concreting gangs were subcontracted and paid on a lump sum basis.

6.4 Analysis of Formwork Labour Productivity

The impact and relative influence of buildability factors on formwork labour productivity of the various observed activities and elements at both, macro and micro levels, were quantified using linear regression analysis. Regression coefficients presented in chapter five were quantified and the relative influence of such variables was determined by the standardisation technique. Such coefficients represent the unique effects of the relevant buildability factors on labour productivity.

Activities observed included setting-out isolated foundation and column axes, isolated foundations, base slabs and floor edges, ground beams, columns, walls and suspended floors, including beams and slab panels. With the exceptions of the variability of footing, ground and suspended beam as well as column sizes, all other hypothesised impacts of buildability factors on labour productivity are statistically significant at 0.050 significance level. Moreover, the Variance Inflation Factors (VIF) amongst the variables are below the cut-off value of 10, indicating reasonable correlations and therefore reliable estimates of the quantified regression coefficients.

It is important to note however that the estimated intercept of the regression model quantifies the average labour productivity when the value of all independent variables in the model is zero [97]. In view of this, the estimated intercepts of all developed regression models in this study are in fact meaningless and bear no practical interpretation.

The impact of all buildability factors on formwork labour productivity are in accordance with the hypothesised effects previously discussed in chapter three. Results of regression analyses of the various observed activities are presented.

6.4.1 Setting-out Isolated Foundation Axes

Before the direct formwork activity of isolated foundations commences, gang members set the axes of the activity. In order to investigate the influence of foundations' grid pattern on labour productivity, the input to this activity was collected separately. The objective of collecting the labour input for the setting-out activity, rather than simply collecting the overall input to foundations formwork, was to unravel the unique effect of grid pattern on labour productivity.

The relationship between labour productivity and foundations grid pattern is determined by the following simple regression model:

$$P\,(No.\ of\ Footings\,/\,mh) = b_0 + b_1\,ALO$$

Where ALO represents the axes layout of isolated foundations and is quantified by the following relationship:

$$ALO = \frac{\textit{Total number of footings}}{\textit{Total number of footing axes}}$$

The relationship between labour productivity and axes setting-out is shown in figure 6.1.

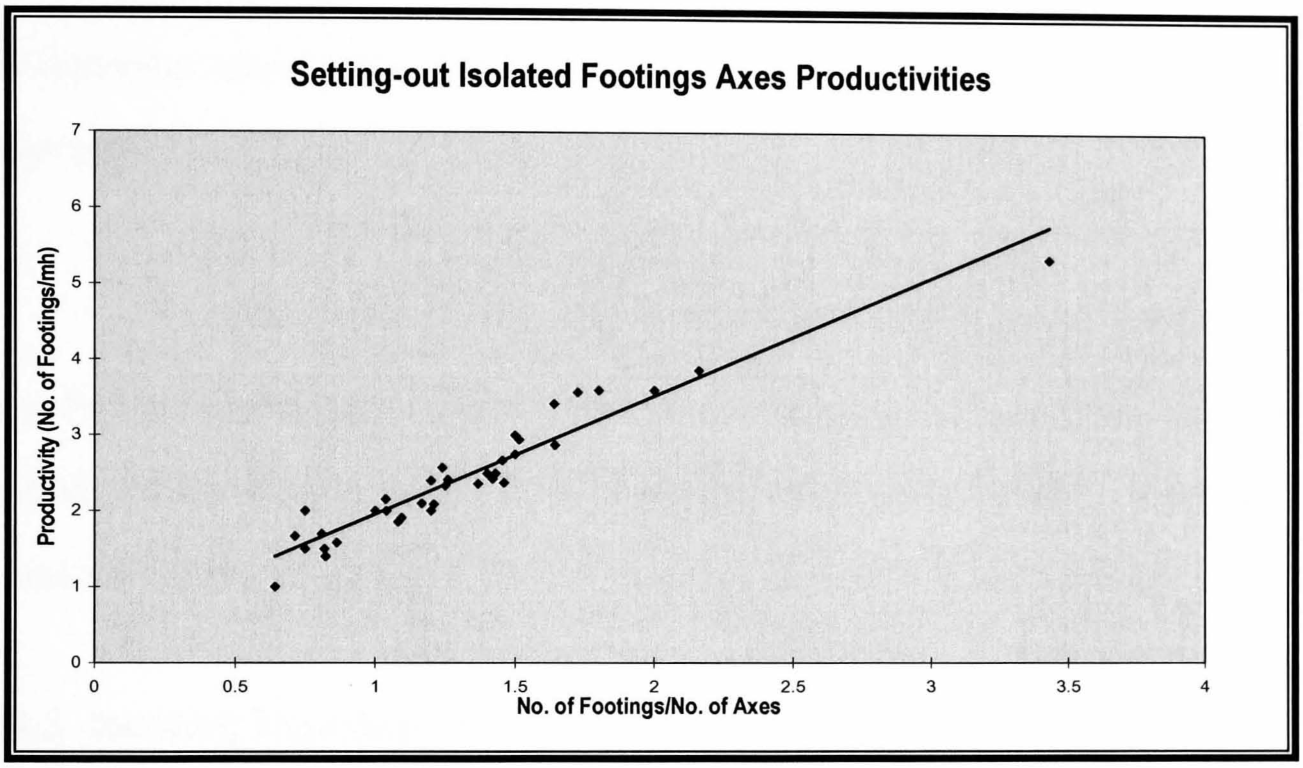


Figure 6.1 Relationship between Labour Productivity and Isolated Foundation Axes Setting-out

The overall regression model and coefficients statistics are presented in tables 6.2 and 6.3 respectively.

Table 6.2 Overall Regression Model Statistics for Isolated Foundations Grid Pattern Effect on Labour Productivity

Correlation Coefficient (R)	*96.10%*
Coefficient of Determination (R^2)	*92.40%*
Standard Error	*0.209*
F(1,47)	*567.83*
p-value	*0.000*
No. of Observations	*49*

Table 6.3 Regression Coefficients Statistics for Isolated Foundations Grid Pattern Effect on Labour Productivity

Coefficient	*Value*	*Standard Error*	*p-value*	*VIF*[1]	*Standardised Coefficient Value*[1]	*Influence Rank*[2]	*Relative Influence*
ALO	*1.56*	*0.0656*	*0.000*	*N/A*	*N/A*	*N/A*	*N/A*

[1]For all regression models, variance inflation factors and standardised regression coefficients are determined when there are two or more independent variables in the regression model.

[2]For all regression models, influence rank and relative influence are determined when there is two or more independent variables in the regression model.

The relationship between labour productivity and foundations grid pattern therefore is presented as shown below:

$$P(No.of\ Footings\ /\ mh) = 0.397 + 1.56\ ALO \qquad \ldots 6.1$$

Since the number of footings is constant within the observed project, the number of axes used to complete the activity is a function of the foundation layout, being minimum for uniform and symmetrical pattern.

6.4.2 Isolated Foundations

A. Macro-Level Observation

Grid pattern, variability of sizes, total shutter area and average shutter area of footings were hypothesised to influence the labour productivity of the formwork activity of isolated foundations. The relationship between these buildability factors and labour productivity is determined by the following multiple regression model:

$$P(m^2\ /\ mh) = b_0 + b_1\ ALO + b_2\ VOF + b_3\ TSA + b_4\ ASA$$

Where ALO, as previously defined, is the ratio of total number of footings to total number of axes; VOF = total number of different footing sizes; TSA = total shutter area of foundations; and ASA = average shutter area of foundations defined as shown below:

$$\frac{\textit{Total shutter area of footings}\,(m^2)}{\textit{Total number of footings}}$$

The overall regression model and coefficients statistics are presented in tables 6.4 and 6.5 respectively.

Table 6.4 Overall Regression Model Statistics for Macro-Level Formwork Labour Productivity of Isolated Foundations

Correlation Coefficient (R)	*96.40%*
Coefficient of Determination (R^2)	*92.90%*
Standard Error	*0.355*
F(4,44)	*145.73*
p-value	*0.000*
No. of Observations	*49*

Table 6.5 Regression Coefficients Statistics for Macro-Level Formwork Labour Productivity of Isolated Foundations

Coefficient	*Value*	*Standard Error*	*p-value*	*VIF*	*Standardised Coefficient Value*	*Influence Rank*	*Relative Influence*
ALO	*0.635*	*0.156*	*0.0002*	*1.99*	*0.230*	*3*	*0.46*
VOF	*-0.00899*	*0.0152*	*0.558*	*1.43*	*-0.0282*	*N/A*[1]	*N/A*
TSA (m^2)	*0.00714*	*0.00146*	*0.000*	*4.58*	*0.417*	*2*	*0.84*
ASA (m^2)	*0.353*	*0.0449*	*0.000*	*2.50*	*0.496*	*1*	*1.00*

[1]Influence rank and relative influence of only significant buildability factors, i.e. p-value < 0.050, on labour productivity were quantified.

The relationship between formwork labour productivity of isolated foundations and the relevant buildability factors at the macro-level is determined by the following multiple regression model:

$$P(m^2/mh) = 0.345 + 0.635\,ALO - 0.00899\,VOF + 0.00714\,TSA + 0.353\,ASA \quad ...6.2$$

The largest absolute value of the standardised regression coefficients indicates the most influential buildability factor, i.e. influence rank, on labour productivity. In order to determine the relative influence of such factors, the most influential factor was chosen to form the base or reference factor, and was assigned the value of 1.00. The relative influence of each factor was then measured relative to the reference factor as follows:

$$\textit{Relative influence of the } k^{th} \textit{ factor} = \frac{\textit{Standardised coefficient value of the } k^{th} \textit{ factor}}{\textit{Standardised coefficient value of the reference factor}}$$

The regression coefficient algebraic sign indicates the direction of the influence of buildability factor on labour productivity, i.e. positive or negative.

B. Micro-Level Observation

The shutter area of the observed footing is the relevant buildability factor at the micro-level. The relationship between formwork labour productivity and the shutter area is determined by the following simple regression model:

$$P\,(m^2/mh) = b_0 + b_1\,SA$$

Where SA = the shutter area of the observed footing.

The relationship between labour productivity and the shutter area of isolated foundations is shown in figure 6.2.

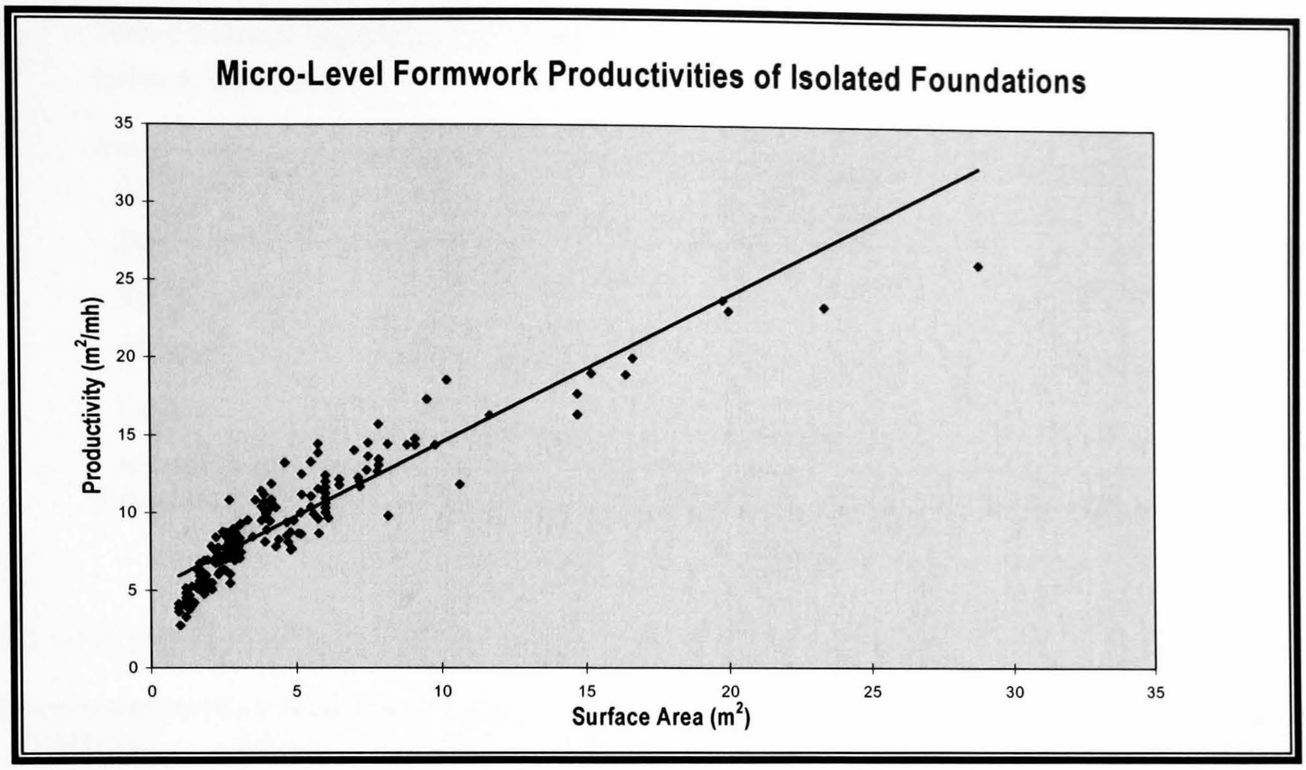


Figure 6.2 Relationship between Labour Productivity and Shutter Area of Isolated Foundations

Figure 6.2 shown above reveals an interesting pattern. We have previously discussed in chapter four some productivity data points which could be classified as outliers, and found a common factor amongst them; they were all associated with large outputs, therefore, none was discarded from the analysis. The linear regression method chosen for the analysis phase of this project assumes a linear relationship between the dependent factor and the independent factor(s), i.e. labour productivity and buildability factor(s). The pattern depicted in figure 6.2 indicates that the actual relationship is more complex than the assumed linear pattern, and that a non-linear relationship, i.e. a curve, would be a better fit than a straight line. This finding further validates the decision not to exclude such points from the analysis. However, the quantified results based on the assumed linear relationship show that such a relationship is adequate enough to model and quantify the influence of buildability factors on labour productivity with reasonable accuracy.

The overall regression model and coefficients statistics are presented in tables 6.6 and 6.7 respectively.

Table 6.6 Overall Regression Model Statistics for Micro-Level Formwork Labour Productivity of Isolated Foundations

Correlation Coefficient (R)	*91.50%*
Coefficient of Determination (R^2)	*83.70%*
Standard Error	*1.64*
F(1,205)	*1052.51*
p-value	*0.000*
No. of Observations	*207*

Table 6.7 Regression Coefficients Statistics for Micro-Level Formwork Labour Productivity of Isolated Foundations

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
SA (m^2)	*0.951*	*0.0293*	*0.000*	*N/A*	*N/A*	*N/A*	*N/A*

The relationship between labour productivity and the shutter area of isolated foundations is quantified by the following regression model:

$$P(m^2 / mh) = 5.03 + 0.951 SA \qquad \text{...6.3}$$

6.4.3 Base Slabs and Floor Edges

Raft foundations, ground slabs and floor edges formwork activities were observed at the macro-level. As we have previously indicated in chapter three, plywood sheets were used in the formwork activity of raft foundations whereas assembled timber boards were used in ground slabs and floor edges. Unlike plywood sheets, timber boards require additional labour input to be assembled to the required size. Therefore, in order to minimise the impact of material type, and unravel the influence of buildability factors on labour productivity, two separate analyses were conducted, i.e. raft foundations versus ground slabs and floor edges.

Since the formwork activity of base slabs and floor edges do not involve individual elements which could also be monitored at the micro-level, observation of this activity was limited to the macro-level.

A. Raft Foundations

Two variables were hypothesised to affect formwork labour productivity of this activity: the total shutter area and the geometric factor. The relationship between labour productivity and the independent variables is expressed by the following multiple regression model:

$$P(m^2 / mh) = b_0 + b_1\, TSA + b_2\, GF$$

Where TSA = total shutter area; and GF = geometric factor quantified as shown below:

$$GF = \frac{\text{Total number of angels around the perimeter}}{\text{Total perimeter length}(m)} \qquad \ldots 6.4$$

The overall regression model and coefficients statistics are shown in tables 6.8 and 6.9 respectively.

Table 6.8 Overall Regression Model Statistics for Formwork Labour Productivity of Raft Foundations

Correlation Coefficient (R)	*87.00%*
Coefficient of Determination (R^2)	*75.80%*
Standard Error	*0.244*
F(2,31)	*48.55*
p-value	*0.000*
No. of Observations	*34*

Table 6.9 Regression Coefficients Statistics for Formwork Labour Productivity of Raft Foundations

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
TSA (m^2)	*0.00396*	*0.000925*	*0.000169*	*1.35*[1]	*0.439*	*2*	*0.78*
GF	*-4.62*	*0.845*	*0.000*		*-0.561*	*1*	*1.00*

[1]Variance inflation factor indicating the correlation between total shutter area and geometric factor in the model.

The relationship between formwork labour productivity of raft foundations and the relevant buildability factors is determined by the following multiple regression model:

$$P(m^2 / mh) = 1.96 + 0.00396\, TSA - 4.62\, GF \qquad \ldots 6.5$$

B. Ground Slabs and Floor Edges

As the case with raft foundations, the same buildability factors, i.e. total shutter area and geometric factor, were hypothesised to influence the formwork labour productivity of ground slabs as well as floor edges. The relationship between labour productivity and the independent variables is quantified by the following multiple regression model:

$$P(m^2 / mh) = b_0 + b_1\, TSA + b_2\, GF$$

Where TSA = total shutter area; and GF = geometric factor quantified as previously shown in equation 6.4.

The overall regression model and coefficients statistics are shown in tables 6.10 and 6.11 respectively.

Table 6.10 Overall Regression Model Statistics for Formwork Labour Productivity of Ground Slabs and Floor Edges

Correlation Coefficient (R)	*86.82%*
Coefficient of Determination (R^2)	*75.40%*
Standard Error	*0.166*
F(2,220)	*336.68*
p-value	*0.000*
No. of Observations	*223*

Table 6.11 Regression Coefficients Statistics for Formwork Labour Productivity of Ground Slabs and Floor Edges

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
TSA (m^2)	*0.00882*	*0.000711*	*0.000*	*1.07*	*0.430*	*2*	*0.66*
GF	*-1.13*	*0.0600*	*0.000*		*-0.652*	*1*	*1.00*

The relationship between formwork labour productivity of raft foundations and the relevant buildability factors is quantified by the following multiple regression model:

$$P(m^2 / mh) = 1.46 + 0.00882\,TSA - 1.13\,GF \qquad \text{...6.6}$$

Consistent with the results obtained from the analysis of raft foundations, the geometric factor has the larger influence on formwork labour productivity of ground slabs and floor edges.

6.4.4 Ground Beams

A. Macro-Level Observation

Macro-level observation was conducted on formwork activity of ground beams. The buildability factors hypothesised to influence the formwork labour productivity of ground beams were the variability of beam sizes, total shutter area and the total number of joints or beam intersections.

The relationship between labour productivity and the independent buildability factors is quantified by the following regression model:

$$P(m^2 / mh) = b_0 + b_1\,VOB + b_2\,TSA + b_3\,TNJ$$

Where VOB = total number of different ground beam sizes; TSA = total shutter area of beams; and TNJ = total number of joints in beams.

The overall regression model and coefficients statistics are shown in tables 6.12 and 6.13 respectively.

Table 6.12 Overall Regression Model Statistics for Macro-Level Formwork Labour Productivity of Ground Beams

Correlation Coefficient (R)	*93.90%*
Coefficient of Determination (R^2)	*88.20%*
Standard Error	*0.418*
F(3,50)	*124.22*
p-value	*0.000*
No. of Observations	*54*

Table 6.13 Regression Coefficients Statistics for Macro-Level Formwork Labour Productivity of Ground Beams

Coefficient	Value	Standard Error	p-value	VIF	Standardised Coefficient Value	Influence Rank	Relative Influence
VOB	-0.00297	0.0815	0.971	1.10	-0.00186	N/A	N/A
TSA (m^2)	0.00720	0.000405	0.000	1.53	1.07	1	1.00
TNJ	-0.0203	0.00466	0.000	1.66	-0.273	2	0.26

The relationship between formwork labour productivity of ground beams and the relevant buildability factors at the macro-level is quantified by the following multiple regression model:

$$P(m^2/mh) = 3.12 - 0.00297\,VOB + 0.00720\,TSA - 0.0203\,TNJ \qquad ...6.7$$

B. Micro-Level Observation

The major factors affecting formwork labour productivity at this level are the shutter area and number of joints within the monitored beams. The relationship between labour productivity and these factors at the micro-level is quantified by the following multiple regression model:

$$P(m^2/mh) = b_0 + b_1\,SA + b_2\,NJ$$

Where SA = shutter area of the observed beam; and NJ = number of joints within the observed beam.

The overall regression model and coefficients statistics are shown in tables 6.14 and 6.15 respectively.

Table 6.14 Overall Regression Model Statistics for Micro-Level Formwork Labour Productivity of Ground Beams

Correlation Coefficient (R)	*90.22%*
Coefficient of Determination (R^2)	*81.40%*
Standard Error	*1.27*
F(2,331)	*724.04*
p-value	*0.000*
No. of Observations	*334*

Table 6.15 Regression Coefficients Statistics for Micro-Level Formwork Labour Productivity of Ground Beams

Coefficient	Value	Standard Error	p-value	VIF	Standardised Coefficient Value	Influence Rank	Relative Influence
SA (m^2)	0.244	0.00642	0.000	1.01	0.908	1	1.00
NJ	-0.242	0.0586	0.000		-0.0987	2	0.11

The relationship between formwork labour productivity of ground beams and the relevant buildability factors at the micro-level is determined by the following multiple regression model:

$$P(m^2 / mh) = 4.58 + 0.244 SA - 0.0987 NJ \qquad ...6.8$$

Consistent with the results obtained from the macro-level analysis of ground beams, of the two variables impacting the formwork labour productivity, the total shutter area has the larger influence on labour productivity.

6.4.5 Setting-out Column Axes

As with isolated foundations, before the direct formwork activity of columns commences, carpenters start the activity by setting-out the columns axes. In an attempt to verify the pattern depicted from the investigation of the influence of foundations grid pattern on setting-out labour productivity, and to check the consistency of the findings between the two activities, i.e. isolated foundations and columns, the input used to complete this activity was also collected separately.

The relationship between labour productivity and columns grid pattern is quantified by the following simple regression model:

$$P(No.\ of\ columns / mh) = b_0 + b_1\ ALO$$

Where ALO represents the axes layout of columns, and quantified by the following relationship:

$$ALO = \frac{Total\ number\ of\ columns}{Total\ number\ of\ column\ axes} \qquad ...6.9$$

The relationship between labour productivity and axes setting-out is shown in figure 6.3.

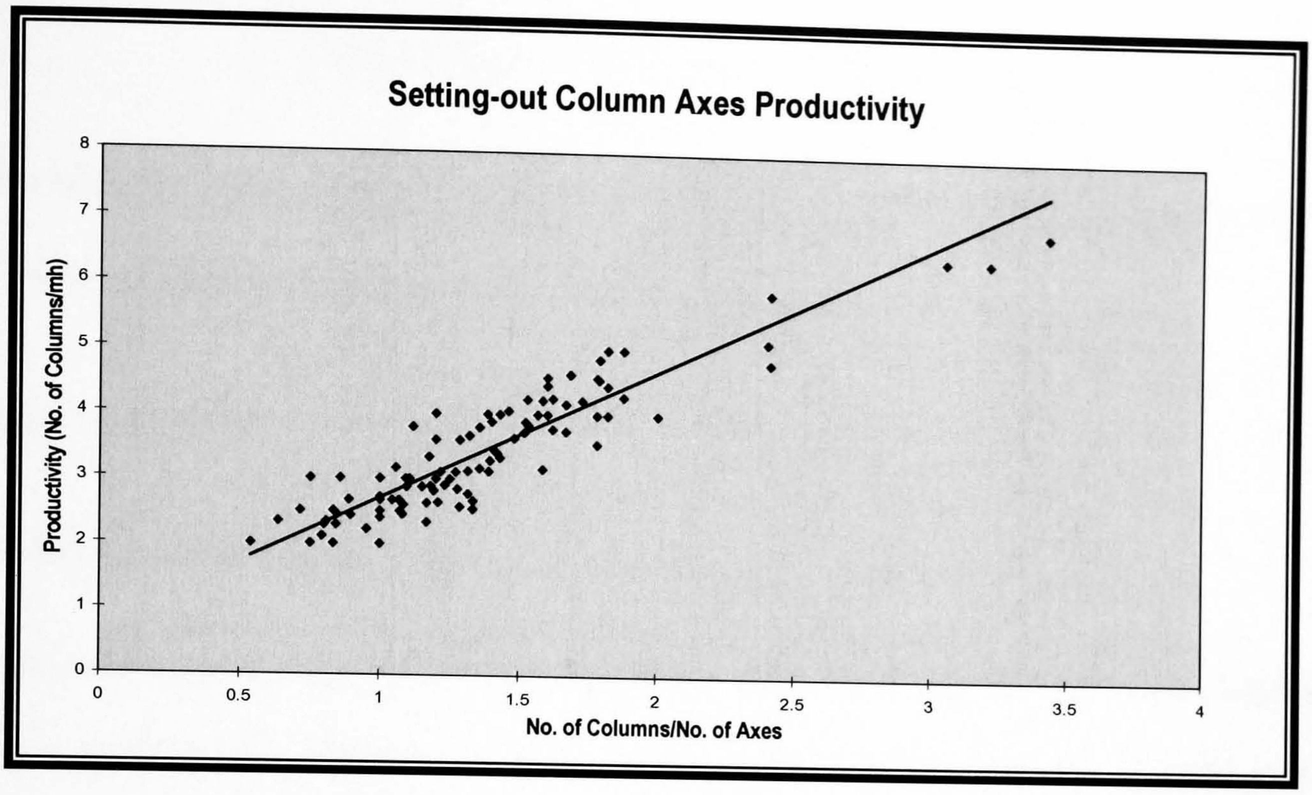


Figure 6.3 Relationship between Labour Productivity and Column Axes Setting-out

The overall regression model and coefficients statistics are presented in tables 6.16 and 6.17 respectively.

Table 6.16 Overall Regression Model Statistics for Columns Grid Pattern Effect on Labour Productivity

Correlation Coefficient (R)	*92.50%*
Coefficient of Determination (R^2)	*85.56%*
Standard Error	*0.365*
F(1,178)	*1054.59*
p-value	*0.000*
No. of Observations	*180*

Table 6.17 Regression Coefficients Statistics for Columns Grid Pattern Effect on Labour Productivity

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
ALO	*1.97*	*0.0606*	*0.000*	*N/A*	*N/A*	*N/A*	*N/A*

The relationship between labour productivity and axes setting-out is given by the following linear regression equation:

$$P\,(No.\,of\,columns\,/\,mh) = 0.741 + 1.97\,ALO \qquad ...6.10$$

This finding is consistent with the results obtained from the investigation of grid pattern effect on the labour productivity of setting-out isolated foundation axes.

6.4.6 Columns

A. Macro-Level Observation

Macro-level measurements were made on formwork productivity of columns. The major buildability factors hypothesised to influence the formwork labour productivity of columns were the grid pattern, variability of column sizes, repetition factor, total shutter area, average shutter area of columns and the percentage of circular columns within the observed columns.

The relationship between labour productivity and the buildability factors is quantified by the following regression model:

$$P\,(m^2\,/\,mh) = b_0 + b_1\,ALO + b_2\,VOC + b_3\,RF + b_4\,TSA + b_5\,ASA + b_6\,PCC$$

Where ALO = the ratio of total number of columns to total number of column axes as shown in equation 6.9; VOC = total number of different column sizes; RF = a dummy variable indicating shutter repetition of columns and quantifying the average difference in labour productivity between repeated and first shuttered columns; TSA = total shutter area of columns; ASA = average shutter area of columns; and PCC = percentage of circular columns within the observed columns quantified as shown below:

$$ASA = \frac{Total\ shutter\ area\ of\ columns\ (m^2)}{Total\ number\ of\ columns}$$

$$PCC = \frac{Total\ shutter\ area\ of\ circular\ columns\ (m^2)}{Total\ shutter\ area\ of\ all\ columns\ (m^2)} * 100$$

The overall regression model and coefficients statistics are shown in tables 6.18 and 6.19 respectively.

Table 6.18 Overall Regression Model Statistics for Macro-Level Formwork Labour Productivity of Columns

Correlation Coefficient (R)	*91.25%*
Coefficient of Determination (R^2)	*83.26%*
Standard Error	*0.317*
F(6,175)	*145.10*
p-value	*0.000*
No. of Observations	*182*

Table 6.19 Regression Coefficients Statistics for Macro-Level Formwork Labour Productivity of Columns

Coefficient	*Value*	*Standard Error*	*p-value*	*VIF*	*Standardised Coefficient Value*	*Influence Rank*	*Relative Influence*
ALO	0.444	0.0682	0.000	1.67	0.260	3	0.60
VOC	-0.00360	0.00798	0.652	1.48	-0.0169	N/A	N/A
RF	-0.167	0.0610	0.00674	1.37	NA[1]	N/A	N/A
TSA (m^2)	0.00146	0.000378	0.000	2.59	0.193	4	0.44
ASA (m^2)	0.157	0.0181	0.000	1.82	0.362	2	0.83
PCC	-0.0124	0.00113	0.000	1.64	-0.434	1	1.00

[1]Dummy variables are used to quantify differences in levels between or amongst categories, therefore, the normal interpretation for standardised coefficients does not apply.

The overall multiple regression model quantifying the relationship between macro-level formwork labour productivity of columns and the relevant buildability factors is shown below:

$$\begin{aligned} P\,(m^2/mh) = 1.13 + 0.444\,ALO - 0.00360\,VOC - 0.167\,RF \\ + 0.00146\,TSA + 0.157\,ASA - 0.0124\,PCC \end{aligned} \quad ...6.11$$

The influence of columns shutter repetition on labour productivity was quantified using a dummy variable with the following two values: 1 for the first time the shutter is erected, 0 otherwise. The regression coefficient value of the dummy variable shown in table 6.19, quantifies the average difference in labour productivity between the two shutter repetition categories of columns. In view of the previous discussion, the average difference in formwork labour productivity between first and repeated shutter of columns is -0.167 m^2/mh. The negative sign indicates that, on average, the labour productivity of first shuttered columns is less than that of repeated shuttered columns.

The average percentage increase in labour productivity due to shutter repetition effect is quantified by substituting the average values shown in table 6.20 of the independent buildability factors obtained from the total number of observations into equation 6.11 for the two categories of the dummy variables, i.e. 0 and 1, as follows:

Table 6.20 Average Values of Buildability Factors Influencing Macro-Level Formwork Labour Productivity of Columns

Independent Design Variable	***Average Value***
ALO	*1.48*
VOC	*6.55*
TSA (m^2)	*146.40*
ASA (m^2)	*5.50*
PCC (%)	*9.86*

1. First Shuttered Columns, RF = 1:

$$\begin{aligned} P(m^2/mh) = 1.13 &+ 0.444\,(1.48) - 0.00360\,(6.55) \\ &- 0.167\,(1) + 0.00146\,(146.40) \\ &+ 0.157\,(5.50) - 0.0124\,(9.86) = 2.55 \end{aligned}$$

2. Repeated Shuttered Columns, RF = 0:

$$\begin{aligned} P(m^2/mh) = 1.13 &+ 0.444\,(1.48) - 0.00360\,(6.55) \\ &- 0.167\,(0) + 0.00146\,(146.40) \\ &+ 0.157\,(5.50) - 0.0124\,(9.86) = 2.72 \end{aligned}$$

The average percentage increase in formwork labour productivity of columns due to shutter repetition is therefore quantified as follows:

$$\left[\frac{(2.72-2.55)}{2.55}\right]*100=6.67\% \qquad \ldots 6.12$$

Thus, and holding all other variables in the model constant, shutter repetition in columns yields, on average, approximately 7% increase in formwork labour productivity.

The relative influence of buildability factors of this activity reveals interesting findings. The complexity involved with shuttering circular columns overshadowed the influence of all other design variables. It is also an interesting finding that the average shutter area is more influential than the total shutter area of columns on labour productivity. As we have previously hypothesised in chapter three, this confirms the argument that the actual effect of shutter area is more dependent on the average than the total shutter area of all elements combined. This pattern was also obvious in isolated foundations.

B. Micro-Level Observation

Micro-level observation was conducted on formwork labour productivity of columns. At this level, the direct shuttering process involved fixing pre-assembled sides, plumbing and bracing. Thus, grid pattern, variability of column sizes and repetition factor have no influence on the micro-level labour productivity.

The major buildability factors hypothesised to impact the labour productivity at the micro-level are the shutter area as well as the geometry of the observed column, i.e. rectangular versus circular.

The relationship between labour productivity and buildability factors at this level is quantified by the following multiple regression model:

$$P(m^2/mh)=b_0+b_1\,SA+b_2\,CGeom$$

Where SA = shutter area of the observed column; and CGeom = a dummy variable indicating the geometry of the observed column and quantifying the average difference in labour productivity between the two categories of columns. The value of 0 is selected to represent rectangular columns whereas the value of 1 is used for circular columns.

The overall regression model and coefficients statistics are shown in tables 6.21 and 6.22 respectively.

Table 6.21 Overall Regression Model Statistics for Micro-Level Formwork Labour Productivity of Columns

Correlation Coefficient (R)	*91.80%*
Coefficient of Determination (R^2)	*84.27%*
Standard Error	*0.453*
F(2,733)	*1964.38*
p-value	*0.000*
No. of Observations	*736*

Table 6.22 Regression Coefficients Statistics for Micro-Level Formwork Labour Productivity of Columns

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
SA (m^2)	*0.379*	*0.00767*	*0.000*	*1.05*	*0.742*	*N/A*	*N/A*
CGeom	*-0.955*	*0.0356*	*0.000*		*N/A*	*N/A*	*N/A*

The relationship between formwork labour productivity of columns and the relevant buildability factors at the micro-level is therefore quantified by the following multiple regression model:

$$P(m^2/mh) = 2.41 + 0.379\,SA - 0.955\,CGeom \qquad \text{...6.13}$$

As shown in equation 6.13 above, the average difference in labour productivity between shuttering circular and rectangular columns is -0.955 m^2/mh.

The total number of observations made for this activity was 736. Of which, 471 rectangular and 265 circular columns were observed. Table 6.23 expresses the average values of observed shutter areas of the two categories.

Table 6.23 Average Shutter Areas of Rectangular and Circular Observed Columns

Column Geometry	*Total No. of Observation*	*Average shutter area (m^2)*
Rectangular	*471*	*5.84*
Circular	*265*	*4.82*
Total	*736*	*5.47*

As shown in table 6.23, the rectangular column is the dominant category with a total of 471 observations versus 265 for circular columns. To quantify the average percentage difference in labour productivity between shuttering circular and rectangular columns, the column average area of each category is substituted into equation 6.13 as follows:

1. **Circular Columns, CGeom = 1**

$$P\,(m^2 / mh) = 2.41 + 0.379\,(4.82) - 0.955\,(1) = 3.28$$

2. **Rectangular Columns, CGeom = 0:**

$$P\,(m^2 / mh) = 2.41 + 0.379\,(5.84) - 0.955\,(0) = 4.62$$

The average percentage loss in formwork labour productivity associated with shuttering circular columns is therefore quantified as follows:

$$\left[\frac{(4.62 - 3.28)}{4.62}\right] * 100 = 29.00\% \qquad ...6.14$$

It is worth noting, that an interactive regression model incorporating an interaction term between the shutter area and geometry of columns was investigated. The term however, was statistically insignificant in its effect, and therefore, was discarded from the model.

6.4.7 Walls

Macro-level observation was conducted on formwork activity of walls. The major buildability factors hypothesised to impact the formwork labour productivity of walls were the total shutter area as well as the geometric factor of walls.

The relationship between labour productivity and the independent buildability factors is quantified by the following regression model:

$$P(m^2/mh) = b_0 + b_1\,TSA + b_2\,GF$$

Where TSA = total shutter area of walls; and GF = wall geometric factor quantified as follows:

$$GF = \frac{\text{Total number of angels in wall around the perimeter}}{\text{Total perimeter length of wall } (m)}$$

The overall regression model and coefficients statistics are shown in tables 6.24 and 6.25 respectively.

Table 6.24 Overall Regression Model Statistics for Formwork Labour Productivity of Walls

Correlation Coefficient (R)	*89.04%*
Coefficient of Determination (R^2)	*79.28%*
Standard Error	*0.198*
F(2,232)	*443.80*
p-value	*0.000*
No. of Observations	*235*

Table 6.25 Regression Coefficients Statistics for Formwork Labour Productivity of Walls

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
TSA (m^2)	*0.00129*	*0.000*	*0.000*	*1.09*	*0.849*	*1*	*1.00*
GF	*-0.251*	*0.0655*	*0.000*		*-0.119*	*2*	*0.14*

The relationship between formwork labour productivity of walls and the relevant factors is determined by the following multiple regression model:

$$P(m^2/mh) = 2.11 + 0.00129TSA - 0.251GF \qquad ...6.15$$

6.4.8 Suspended Floors

Formwork activity of suspended floors was observed against the independent buildability factors hypothesised to influence the labour productivity at the macro-level. The major investigated factors included the variability of beam sizes, repetition of floors, floor area, average slab panel area, total number of joints in beams, beam floor ratio, percentages of curved beams and non-rectangular slab panels in floors.

The relationship between labour productivity and the independent buildability factors is quantified by the following multiple regression model:

$$P(m^2/mh) = b_0 + b_1 VOB + b_2 RF + b_3 FA + b_4 APA + b_5 TNJ + b_6 BFR \\ + b_7 PCB + b_8 PNRP$$

Where VOB = total number of different beam sizes in floor; RF = a dummy variable indicating forms repetition of floor and quantifying the average difference in productivity between repeated and first formed floors; FA = total floor area; APA = average slab panel area in floor; TNJ = total number of joints in beams; BFR = beam-floor ratio; PCB = percentage of curved beams in floor; and PNRP = percentage of non-rectangular slab panels in floor.

Forms repetition factor, RF, assumes the following two values: 0 for the first time the floor formwork is erected, and 1 otherwise. Average panel area, APA, is quantified by the following expression:

$$\frac{\text{Floor area}(m^2)}{\text{Total number of slab panels within the floor}}$$

Beam-floor ratio is defined as follows:

$$\frac{\textit{Total shutter area of beams in floor } (m^2)}{\textit{Total "usable" floor area } (m^2)}$$

The percentage of curved beams in floor is determined as shown below:

$$\frac{\textit{Total shutter area of curved beams in floor } (m^2)}{\textit{Total shutter area of all beams in floor } (m^2)} * 100$$

And the percentage of non-rectangular slab panels in floor is given by:

$$\frac{\textit{Total shutter area of non-rectangualar slab panels in floor } (m^2)}{\textit{Total shutter area of all panels in floor } (m^2)} * 100$$

The overall regression model and coefficients statistics are shown in tables 6.26 and 6.27 respectively.

Table 6.26 Overall Regression Model Statistics for Macro-Level Formwork Labour Productivity of Suspended Floors

Correlation Coefficient (R)	*90.10%*
Coefficient of Determination (R^2)	*81.16%*
Standard Error	*0.844*
F(8,171)	*92.08*
p-value	*0.000*
No. of Observations	*180*

Table 6.27 Regression Coefficients Statistics for Macro-Level Formwork Labour Productivity of Suspended Floors

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
VOB	*-0.0163*	*0.00884*	*0.067*	*2.81*	*-0.103*	*N/A*	*N/A*
RF	*0.536*	*0.136*	*0.000*	*1.16*	*N/A*	*N/A*	*N/A*
FA (m^2)	*0.00103*	*0.000215*	*0.000*	*2.21*	*0.235*	*3*	*0.57*
APA (m^2)	*0.00423*	*0.000453*	*0.000*	*1.79*	*0.414*	*1*	*1.00*
TNJ	*-0.0117*	*0.00313*	*0.000*	*1.85*	*-0.169*	*4*	*0.41*
BFR	*-1.72*	*0.237*	*0.000*	*2.15*	*-0.352*	*2*	*0.85*
PCB	*-0.0209*	*0.00891*	*0.0203*	*1.47*	*-0.0944*	*6*	*0.23*
PNRP	*-0.00700*	*0.00285*	*0.0151*	*1.67*	*-0.105*	*5*	*0.25*

The relationship between formwork labour productivity of suspended floors and the relevant buildability factors at the macro-level is determined by the following multiple regression model:

$$\begin{aligned} \boldsymbol{P\,(m^2\ /\ mh\,) = 3.98 - 0.0163\ VOB + 0.536\ RF + 0.00103\ FA} \\ \boldsymbol{+\,0.00423\ APA - 0.0117\ TNJ - 1.72\ BFR} \\ \boldsymbol{-\,0.0209\ PCB - 0.00700\ PNRP} \end{aligned} \qquad \ldots 6.16$$

The influence of floor repetition on formwork labour productivity is quantified using a dummy variable which assumes the following two values: 0 for the first time the floor formwork is erected, and 1 otherwise. The regression coefficient value of the dummy variable shown in table 6.27, quantifies the average difference in labour productivity between the two categories of floor repetition factor. Thus, the average difference in formwork labour productivity between repeated and first formed floors is 0.536 m^2/mh. The positive sign indicates that, on average, the labour productivity of repeated is higher than first formed floors. To quantify the average percentage difference between the categories, the average values shown in table 6.28 below of the buildability factors will be substituted into equation 6.16 for the two categories of the dummy variables, i.e. 0 and 1, as follows:

Table 6.28 Average Values of Buildability Factors Influencing Macro-Level Formwork Labour Productivity of Suspended Floors

Independent Continuous Design Variable	***Average Value***
VOB	*14.37*
FA (m^2)	*398.67*
APA (m^2)	*65.55*
TNJ	*25.87*
BFR	*0.809*
PCB	*3.16*
PNRP	*19.09*

1. **Repeated Floors, RF = 1:**

$$\begin{aligned}P(m^2/mh) = {} & 3.98 - 0.0163\,(14.37) + 0.536\,(1) + 0.00103\,(398.67) \\ & + 0.00423\,(65.55) - 0.0117\,(25.87) - 1.72\,(0.809) \\ & - 0.0209\,(3.16) - 0.00700\,(19.09) = 3.08\end{aligned}$$

2. **First Formed Floors, RF = 0:**

$$\begin{aligned}P(m^2/mh) = {} & 3.98 - 0.0163\,(14.37) + 0.536\,(0) + 0.00103\,(398.67) \\ & + 0.00423\,(65.55) - 0.0117\,(25.87) - 1.72\,(0.809) \\ & - 0.0209\,(3.16) - 0.00700\,(19.09) = 2.54\end{aligned}$$

Thus, the average percentage difference in labour productivity between the two repetition factor categories is expressed as follows:

$$\left[\frac{(3.08 - 2.54)}{2.54}\right] * 100 = 21.26\% \qquad \ldots 6.17$$

On average, approximately 21% increase in formwork labour productivity is associated with repeated compared to first formed floors.

Again, as we have previously hypothesised, the average slab panel area in floors overshadowed the influence of all other buildability factors. This finding further confirms the important impact of this variable on formwork labour productivity. Although formwork activities of non-rectangular slab panels as well as curved beams are associated with substantial additional inputs, they have the least impact on the labour productivity of suspended floors. For floors observed at the macro-level, this finding was expected since the percentages of such elements, in comparison with rectangular panels and linear beams are usually small. In fact, the average percentages of non-rectangular slab panels and curved beams in the observed floors are 19.09% and 3.16% respectively.

6.4.9 Suspended Beams

Micro-level observation of suspended beams in floors was conducted where the direct activity of assembling soffits and sides, as well as fixing and securing beams in positions were monitored. Since the direct shuttering activities of selected beams were observed, the overall effect of variability of beam sizes has no impact on the labour productivity at this level of observation. Therefore, the major variables hypothesised to influence the formwork labour productivity at this level are the repetition of beam forms, shutter area of beams, number of joints within the observed beams and the geometry of beam span, i.e. linear versus curved.

The relationship between labour productivity and buildability factors at the micro-level is quantified by the following multiple interaction-regression model:

$$\begin{aligned} P(m^2 / mh) = b_0 &+ b_1\, RF + b_2\, SA + b_3\, NJ + b_4\, GOS + b_5\, (GOS * SA) \\ &+ b_6\, (GOS * NJ) + b_7\, (GOS * RF) \end{aligned} \qquad \text{...6.18}$$

Where RF = a dummy variable indicating forms repetition of the observed beam and quantifying the average difference in labour productivity between repeated and first formed beams. The repetition factor assumes the following two values: 0 for the first time the beam formwork is erected, and 1 otherwise; SA = shutter area of the observed beam; NJ = number of joints within the observed beam; and GOS = a dummy variable indicating the span geometry of the observed beam and quantifying the average difference in labour productivity between curved and linear beams. The span geometry is represented by the following two values: 0 if beam is linear in span, and 1 if curved. As we have previously illustrated in chapter three, curved beams are associated with substantial additional input in comparison with linear beams due to the difference and complexity involved in the setting-out and forming process. In view of this, we would hypothesise that the impacts of the buildability factors upon the formwork labour productivity are different for the two types of beams, i.e. linear versus curved. In order to unravel this difference, interaction terms were hypothesised and included in the multiple regression model as shown in equation 6.18.

The interaction terms (GOS * SA) and (GOS * NJ) indicate that the average rate of change or the slope of the shutter area and the number of joints in the observed beams respectively, are different for the two categories represented by the dummy variable GOS, i.e. linear versus curved beams. Moreover, the interaction term (GOS * RF) hypothesises a different impact of forms repetition on labour productivity for the two span geometry of beams.

The overall regression model and coefficients statistics are shown in tables 6.29 and 6.30 respectively.

Table 6.29 Overall Regression Model Statistics for Micro-Level Formwork Labour Productivity of Suspended Beams

Correlation Coefficient (R)	*94.91%*
Coefficient of Determination (R^2)	*90.08%*
Standard Error	*0.979*
F(7,820)	*1064.13*
p-value	*0.000*
No. of Observations	*828*

Table 6.30 Regression Coefficients Statistics for Micro-Level Formwork Labour Productivity of Suspended Beams

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
SA (m^2)	*0.0831*	*0.00188*	*0.000*	*1.19*	*0.531*	*1*	*1.00*
NJ	*-0.305*	*0.0300*	*0.000*	*1.78*	*-0.149*	*2*	*0.28*
RF	*1.43*	*0.104*	*0.000*	*1.27*	*N/A*	*N/A*	*N/A*
GOS	*-4.76*	*0.119*	*0.000*	*2.07*	*N/A*	*N/A*	*N/A*
*(GOS * SA)*	*-0.0691*	*0.00690*	*0.000*	*1.81*	*N/A*	*N/A*	*N/A*
*(GOS * NJ)*	*0.251*	*0.0470*	*0.000*	*2.04*	*N/A*	*N/A*	*N/A*
*(GOS * RF)*	*-0.923*	*0.227*	*0.000*	*1.46*	*N/A*	*N/A*	*N/A*

The interaction regression model representing the relationship between formwork labour productivity and buildability factors is determined by the following equation:

$$\begin{aligned} P(m^2/mh) = {} & 5.46 + 1.43\,RF + 0.0831\,SA - 0.305\,NJ - 4.76\,GOS \\ & - 0.0691\,(GOS * SA) + 0.251\,(GOS * NJ) - 0.923\,(GOS * RF) \end{aligned} \quad \ldots 6.19$$

Based on the quantified model shown in equation 6.19, on average, the positive difference in formwork labour productivity between repeated and first formed beams is 1.43 m^2/mh, holding the shutter area and the number of joints in beams constants, and constraining the span geometry at zero, i.e. linear beams. The reason behind constraining the span geometry at zero is due to the presence of the interaction term involving the span geometry and repetition factor as shown in the model. Labour productivity increases, on average, by 0.0831 m^2/mh, as the shutter area of beams increases by 1.00 m^2, holding the repetition factor and the number of joints constant, and also constraining the span geometry at zero. Labour productivity decreases, on average, by 0.305 m^2/mh, as the number of joints in beams increases by one unit, holding the repetition factor as well as the shutter area of beams constant, and constraining span geometry at zero. The negative difference in average labour productivity between curved and linear beams is 4.76 m^2/mh, constraining the repetition factor, shutter area and the number of joints in beams at zero.

The interaction term between span geometry and shutter area of beams, indicates a significant average reduction of 0.0691 in the slope of the relationship between beam shutter area and labour productivity between curved and linear beams, constraining repetition factor as well as the number of joints in beams at zero. This finding may be attributed to the complexity associated with shuttering curved beams and reflected through the reduction in the intensity of the influence of beam shutter areas on formwork labour productivity of suspended beams.

The interaction between span geometry and number of joints in beams reveals a significant increase of 0.251 in the slope of the relationship between labour productivity and the number of joints in beams between curved and linear beams, constraining repetition factor and shutter area of beams at zero, i.e. there is a decrease in the negative intensity of the influence of number of joints in beams on labour productivity. This significant positive shift in slope could be explained by the fact that as the joints in curved beams increases, the effective curved span of beams decreases. It would then be reasonable to assume that it becomes easier for carpenters to handle, bend and fix fibreboard beam sides in place to the required arc-lengths.

The final interaction term between span geometry and repetition factor quantifies the average difference in labour productivity between curved beams having repeated forms and first formed linear beams, constraining the shutter area as well as the number of joints in beams at zero. The negative sign indicates that the labour productivity of curved beams, even with repeated forms is, on average, significantly lower by 0.923 m^2/mh than first formed linear beams.

The total number of observations made for suspended beams activity was 828. Of which, 653 linear and 175 curved beams were monitored. Table 6.31 presents the average values of observed shutter areas and number of joints for the two categories of beams.

Table 6.31 Average Values of Buildability Factors Influencing Micro-Level Formwork Labour Productivity of Observed Linear and Curved Suspended Beams

Span Geometry	***Total No. of Observation***	***Average shutter area (m^2)***	***Average Number of Joints***
Linear	*653*	*18.49*	*0.95*
Curved	*175*	*10.05*	*0.99*
Total	*828*	*16.70*	*0.96*

Since the interaction regression model involves two qualitative dummy variables quantifying the effects of both; repetition factor and span geometry on labour productivity, the average percentage difference in labour productivity due to forms repetition and span geometry would be quantified by substituting the corresponding average values shown in table 6.31 of the continuous buildability factors obtained from the total number of observations into equation 6.19 for each category of span geometry and forms repetition as follows:

A. Quantifying Average Percentage Difference in Labour Productivity due to Repetition Effect in Linear Beams

The average labour productivities of first and repeated formed linear beams respectively are quantified as follows:

$$P(m^2/mh) = 5.46 + 1.43(0) + 0.0831(18.49) - 0.305(0.95) - 4.76(0)$$
$$- 0.0691(0*18.46) + 0.251(0*0.95) - 0.923(0*0) = 6.71$$

$$P(m^2/mh) = 5.46 + 1.43(1) + 0.0831(18.49) - 0.305(0.95) - 4.76(0)$$
$$- 0.0691(0*18.49) + 0.251(0*0.95) - 0.923(0*1) = 8.14$$

Thus, the average percentage difference in labour productivity between the two repetition factor categories for linear beams can be expressed as shown below:

$$\left[\frac{(8.14 - 6.71)}{6.71}\right]*100 = 21.31\% \qquad ...6.20$$

Hence, a gain in formwork labour productivity of approximately 21% is estimated between repeated and first formed linear beams.

B. Quantifying Average Percentage Difference in Labour productivity due to Repetition Effect in Curved Beams

The average labour productivities of first and repeated formed curved beams respectively are quantified as follows:

$$P(m^2/mh) = 5.46 + 1.43(0) + 0.0831(10.05) - 0.305(0.99) - 4.76(1)$$
$$- 0.0691(1*10.05) + 0.251(1*0.99) - 0.923(1*0) = 0.79$$

$$P(m^2/mh) = 5.46 + 1.43(1) + 0.0831(10.05) - 0.305(0.99) - 4.76(1)$$
$$- 0.0691(1*10.05) + 0.251(1*0.99) - 0.923(1*1) = 1.29$$

Hence, the average percentage difference in labour productivity between the two repetition factor categories for curved beams is expressed as shown below:

$$\left[\frac{(1.29 - 0.79)}{0.79}\right]*100 = 63.30\% \qquad ...6.21$$

Thus, a gain in formwork labour productivity of about 63% is estimated as a result of forms repetition in curved beams. This major difference in labour productivity gain due to forms repetition in curved beams in comparison with linear beams, i.e. 63% versus 21%, was expected and in accordance with the hypothesised different impact of forms repetition on the two categories of span geometry. In comparison with linear beams, the substantial additional labour inputs associated with setting-out, measurements, cuttings and assembling curved beam soffits and sides would be saved as a result of forms repetition.

C. Quantifying Average Percentage Difference in Labour Productivity due to Span Geometry in First Formed Beams

The average labour productivities of first formed linear and curved beams respectively are quantified as follows:

$$\begin{aligned} P(m^2/mh) = {} & 5.46 + 1.43(0) + 0.0831(18.49) - 0.305(0.95) - 4.76(0) \\ & - 0.0691(0*18.49) + 0.251(0*0.95) - 0.923(0*0) = 6.71 \end{aligned}$$

$$\begin{aligned} P(m^2/mh) = {} & 5.46 + 1.43(0) + 0.0831(10.05) - 0.305(0.99) - 4.76(1) \\ & - 0.0691(1*10.05) + 0.251(1*0.99) - 0.923(1*0) = 0.79 \end{aligned}$$

Hence, the average percentage difference in formwork labour productivity between first formed curved and linear beams can be expressed as shown below:

$$\left[\frac{(6.71-0.79)}{6.71}\right]*100 = 88.23\% \qquad \text{...6.22}$$

For first formed beams, in comparison with the linear type, an average percentage loss of approximately 88% in formwork labour productivity is associated with curved beams.

D. Quantifying average percentage difference in labour productivity due to Span Geometry in Repeated Formed Beams

The average labour productivities of repeated formed linear and curved beams respectively are quantified as shown below:

$$P(m^2/mh) = 5.46 + 1.43(1) + 0.0831(18.46) - 0.305(0.95) - 4.76(0)$$
$$- 0.0691(0*18.46) + 0.251(0*0.95) - 0.923(0*1) = 8.13$$

$$P(m^2/mh) = 5.46 + 1.43(1) + 0.0831(10.05) - 0.305(0.99) - 4.76(1)$$
$$- 0.0691(1*10.05) + 0.251(1*0.99) - 0.923(1*1) = 1.29$$

Thus, the average percentage difference in formwork labour productivity between repeated formed curved and linear beams is expressed as follows:

$$\left[\frac{(8.13 - 1.29)}{8.13}\right] * 100 = 84.13\% \qquad \text{...6.23}$$

For the repeated forms category, compared with linear beams, an average percentage loss of about 84% in formwork labour productivity is associated with curved beams.

It can be noticed from the results that the difference in average percentage loss between curved and linear formwork productivity of beams for the two forms repetition categories is only about 4%, indicating almost a consistency in the average percentage loss in formwork labour productivity due to span geometry of suspended beams.

6.4.10 Suspended Slab Panels

Micro-level observation of suspended slab panels was conducted where the direct activities of fixing bearers, joists and soffits of slabs were monitored. The major buildability factors hypothesised to influence the formwork labour productivity of slab panels are the repetition of forms, panel area and the geometry of the observed panel.

Panel geometry was classified into two categories; rectangular and non-rectangular. The practical explanation for this classification is that it would be difficult to collect the productivity data points required for statistical significance for each geometric shape, i.e. trapezoidal, circular, triangular, etc., for the various slab panel shapes encountered on sites. Therefore, it was decided to lump all non-rectangular panels into a single category to be analysed against the rectangular shape panels.

The relationship between labour productivity of suspended slab panels and buildability factors at the micro-level is quantified by the following multiple interaction-regression model:

$$P(m^2 / mh) = b_0 + b_1\, RF + b_2 A + b_3\, GOP + b_4\, (GOP * RF) \qquad \text{...6.24}$$

Where RF = a dummy variable indicating forms repetition of the observed slab panels and quantifying the average difference in labour productivity between repeated and first formed panels. The repetition factor assumes the following two values: 0 for the first time the slab formwork is erected, and 1 otherwise; A = area of the observed panels; and GOP = a dummy variable indicating the observed slab panel geometry which assumes the following two values: 0 if slab is rectangular, and 1 if non-rectangular.

As we have previously stated in chapter three, non-rectangular panels are associated with additional input in comparison with rectangular panels due to the complexity involved in setting-out, measurement, cutting and forming process. Hence, we would hypothesise that the impact of repetition on labour productivity is different for the two types of panel geometry, i.e. rectangular versus non-rectangular. In order to quantify this difference, an interaction term between the panel geometry and repetition factor was hypothesised and incorporated into the multiple regression model as shown in equation 6.24 above.

The overall regression model and coefficients statistics are shown in tables 6.32 and 6.33 respectively.

Table 6.32 Overall Regression Model Statistics for Micro-Level Formwork Labour Productivity of Suspended Slab Panels

Correlation Coefficient (R)	*87.24%*
Coefficient of Determination (R^2)	*76.11%*
Standard Error	*1.54*
F(4,812)	*646.60*
p-value	*0.000*
No. of Observations	*817*

Table 6.33 Regression Coefficients Statistics for Micro-Level Formwork Labour Productivity of Suspended Slab Panels

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
A (m^2)	*0.0875*	*0.00188*	*0.000*	*1.04*	*0.813*	*N/A*	*N/A*
RF	*0.477*	*0.198*	*0.0165*	*1.69*	*N/A*	*N/A*	*N/A*
GOP	*-1.41*	*0.118*	*0.000*	*1.17*	*N/A*	*N/A*	*N/A*
*(GOP * RF)*	*0.630*	*0.313*	*0.0449*	*1.83*	*N/A*	*N/A*	*N/A*

The interaction regression model representing the relationship between formwork labour productivity and buildability factors is determined by the following equation:

$$P(m^2 / mh) = 3.63 + 0.477\,RF + 0.0875\,A - 1.41\,GOP + 0.630\,(GOP * RF) \qquad ...6.25$$

On average, the positive difference in formwork labour productivity between repeated and first formed panels is 0.477 m^2/mh, holding the panel area constant, and constraining the panel geometry at zero, i.e. rectangular panels. Again, the reason behind constraining the panel geometry at zero is due to the presence of the interaction term involving the panel geometry and repetition factor as shown in the model. Labour productivity increases, on average, by 0.0875 m^2/mh, as the area of panels increases by 1.00 m^2, holding the repetition factor and panel geometry constant. The negative difference or loss in average formwork labour productivity between non-rectangular and rectangular slab panels is 1.41 m^2/mh, holding the area of panels constant and constraining the repetition factor at zero.

The interaction term between span geometry and repetition factor quantifies the average difference in labour productivity between non-rectangular repeated and first formed rectangular slab panels. The positive sign indicates that the labour productivity of non-rectangular repeated panels is, on average, higher by 0.630 m^2/mh than first formed rectangular slab panels.

The total number of observations made for suspended slab panels activity was 817. Of which, 473 rectangular and 344 non-rectangular were monitored. Table 6.34 expresses the average values of the observed panel areas of the two categories.

Table 6.34 Average Values of Observed Slab Panel Areas

Slab Geometry	*Total No. of Observation*	*Average Panel area (m^2)*
Rectangular	*473*	*25.07*
Non-rectangular	*344*	*17.79*
Total	*817*	*22.00*

The average values of the panel areas shown in table 6.34 are used for the corresponding category of panel geometry to quantify the percentage average difference in formwork labour productivity due to repetition factor and panel geometry as follows:

A. Quantifying Average Percentage Difference in Labour Productivity due to Repetition Effect in Rectangular Slab Panels

In order to quantify the average percentage difference in labour productivity between repeated and first formed rectangular slab panels, i.e. GOP = 0, the average rectangular panel area shown in table 6.34 is substituted into equation 6.25 for the relative repetition categories as follows:

1. First Formed Panels, RF = 0:

$$P(m^2/mh) = 3.63 + 0.477(0) + 0.0875(25.07) - 1.41(0) + 0.630(0*0) = 5.82$$

2. **Repeated Formed Panels, RF = 1:**

$$P(m^2/mh) = 3.63 + 0.477(1) + 0.0875(25.07) - 1.41(0) + 0.630(0*1) = 6.30$$

Thus, the average percentage gain in labour productivity of rectangular slab panels due to forms repetition is quantified as shown below:

$$\left[\frac{(6.30 - 5.82)}{5.82}\right]*100 = 8.25\% \qquad ...6.26$$

On average, an increase of approximately 8% in formwork labour productivity of suspended rectangular slab panels is achieved due to forms repetition.

B. Quantifying Average Percentage Difference in Labour Productivity due to Repetition Effect in Non-rectangular Slab Panels

The average percentage difference in labour productivity between repeated and first formed non-rectangular slab panels, i.e. GOP = 1, is quantified by substituting the average non-rectangular panel area shown in table 6.34 into equation 6.25 for the relative repetition categories as follows:

1. **First Formed Panels, RF = 0:**

$$P(m^2/mh) = 3.63 + 0.477(0) + 0.0875(17.79) - 1.41(1) + 0.630(1*0) = 3.78$$

2. **Repeated Formed Panels, RF = 1:**

$$P(m^2/mh) = 3.63 + 0.477(1) + 0.0875(17.79) - 1.41(1) + 0.630(1*1) = 4.88$$

Thus, the average percentage gain in labour productivity of non-rectangular slab panels due to forms repetition is quantified as shown below:

$$\left[\frac{(4.88 - 3.78)}{3.78}\right]*100 = 29.10\% \qquad ...6.27$$

An average increase of about 29% in formwork labour productivity of suspended non-rectangular slab panels is achieved due to forms repetition.

It can be seen from equations 6.26 and 6.27 that the influence of repetition factor on formwork labour productivity in non-rectangular panels is much higher compared with rectangular panels, i.e. 29% versus 8% respectively. This finding is anticipated as we have previously hypothesised a different impact of repetition between non-rectangular and rectangular panels on labour productivity. Substantial saving in setting-out, measurement and cutting inputs associated with forming non-rectangular slab panels is achieved due to forms repetition.

C. Quantifying Average Percentage Difference in Labour Productivity due to Panel Geometry in First Formed Slab Panels

In order to quantify the average percentage difference in labour productivity between first formed non-rectangular and rectangular slab panels, the average panel areas shown in table 6.34 are substituted into equation 6.25 for the relative panel geometry categories as follows:

1. Rectangular Slab Panels, GOP = 0:

$$P(m^2 / mh) = 3.63 + 0.477(0) + 0.0875(25.07) - 1.41(0) + 0.630(0 * 0) = 5.82$$

2. Non-rectangular Slab Panels, GOP = 1:

$$P(m^2 / mh) = 3.63 + 0.477(0) + 0.0875(17.79) - 1.41(1) + 0.630(1 * 0) = 3.78$$

Hence, the average percentage difference in labour productivity between first formed non-rectangular and rectangular panels is quantified as follows:

$$\left[\frac{(5.82 - 3.78)}{5.82}\right] * 100 = 35.05\% \qquad \ldots 6.28$$

In comparison with rectangular slab panels, on average, 35% loss in formwork labour productivity is associated with forming non-rectangular panels.

D. Quantifying Average Percentage Difference in Labour Productivity due to Panel Geometry in Repeated Formed Slab Panels

The average percentage difference in labour productivity between repeated formed non-rectangular and rectangular slab panels, is determined by substituting the average panel areas shown in table 6.34 into equation 6.25 for the relative panel geometry categories as shown below:

1. Rectangular Slab Panels, GOP = 0:

$$P(m^2/mh) = 3.63 + 0.477(1) + 0.0875(25.07) - 1.41(0) + 0.630(0*1) = 6.30$$

2. Non-rectangular Slab Panels, GOP = 1:

$$P(m^2/mh) = 3.63 + 0.477(1) + 0.0875(17.79) - 1.41(1) + 0.630(1*1) = 4.88$$

Thus, the average percentage difference in labour productivity between repeated formed non-rectangular and rectangular panels is quantified as shown below:

$$\left[\frac{(6.30 - 4.88)}{6.30}\right] * 100 = 22.54\% \qquad \text{...6.29}$$

In comparison with rectangular slab panels, an average of approximately 23% loss in formwork labour productivity is associated with forming non-rectangular panels.

It can be seen from equations 6.28 and 6.29 that approximately 12% of the average difference in labour productivity between repeated formed non-rectangular and rectangular panels has been recovered due to forms repetition effect.

6.5 Summary

The impacts and relative influence of buildability factors on formwork labour productivity of the various observed activities at both levels, macro and micro, were determined using the ordinary least squares method. Regression and coefficients statistics at 0.050 level of significance for the developed models were presented in table format. The unique impact and interaction effects of the relevant buildability factors on labour productivity were quantified and the relative influence of factors was determined using standardised regression coefficients. The major findings of this investigation are summarised as follows:

1. The grid pattern of isolated foundations and columns had a significant impact on the labour productivity of axes setting-out activity. Symmetrical and uniform grid patterns were associated with higher labour productivity than irregular and scattered pattern.

2. A direct significant relationship between shutter area and labour productivity was determined in all observed activities. Higher labour productivity was consistently associated with larger shutter area.

3. The influence of shutter area on labour productivity of activities comprised either individual elements such as isolated foundations and columns, or slab panels contained within the overall floor activities was exposed using the average shutter area of the monitored elements. Higher labour productivity was associated with larger average shutter area. Moreover, the impact of the average shutter area on labour productivity was consistently stronger than the total shutter area for all relevant elements.

4. The influence of column geometry, i.e. circular versus rectangular, on formwork labour productivity was investigated at the macro and micro-levels, and the results were consistent. On average, a loss in labour productivity of 29%, compared with rectangular columns, was associated with forming circular columns.

5. Although the variability of element sizes within the activity had a negative impact on labour productivity, its influence was not statistically significant. This pattern was consistent amongst all relevant elements.

6. Perimeter Geometry had a significant negative effect on formwork labour productivity of raft foundations, ground slabs, floor edges and walls. Perimeter geometry was quantified as the ratio of the total number of angles on the perimeter divided by the perimeter length.

7. The presence of dropped beams had an adverse influence on formwork labour productivity. The impact of beams on labour productivity was quantified by introducing the beam-floor ratio variable. The beam-floor ratio was defined as the total shutter area of dropped beams divided by the floor area supported by those beams. As the beam-floor ratio increases, labour productivity significantly decreases.

8. On average, there was a loss of 88% and 84% in labour productivity associated with first and repeated shuttered beams respectively in curved beams compared to linear beams.

9. Shutter interruption results when framing plans are designed in such a way in which beams, whether ground or suspended, are used to support other beams rather than using either columns or walls for supports. In such cases, openings of the same dimensions of the supported beams are created in the sides of the supporting beams. Formwork Labour productivity of supporting beams was significantly affected by the number of such joints or intersections. As the number of joints in beams increases, labour productivity significantly decreases. This pattern was consistent at both observation levels; macro and micro.

10. An average loss of 35% and 23% in labour productivity associated with first and repeated shuttered slab panels respectively was incurred in non-rectangular panels compared to rectangular panels.

11. The material repetition effect on framing plans of floors and columns observed at the macro level, as well as on elements monitored at the micro-level such as beams and slab panels, had a

significant positive impact on formwork labour productivity. For floors, there was a 21% gain in average labour productivity due to the effect of repetition. For columns, the gain was approximately 7%. The repetition factor was also significant in linear and curved beams. However, due to the complexity involved in forming curved beams, the saving achieved as a result of repetition was higher in curved in comparison with linear beams. On average, the increase in labour productivity was approximately 21% and 63% due to the repetition effect on linear and curved beams respectively. This pattern was realised in forming slab panels too. The repetition impact on labour productivity was, on average, higher in non-rectangular compared with rectangular panels. An average of 8% gain in labour productivity was achieved in rectangular panels whereas approximately 29% increase in labour productivity was achieved in non-rectangular panels as a result of repetition.

Chapter Seven

Analysis of Reinforcing Steel Productivity

7.1 Introduction

Buildability factors hypothesised to influence fixing reinforcing steel labour productivity of the various observed activities were introduced and discussed in chapter three. In this chapter, the impact and relative influence of such factors on reinforcing steel fixing labour productivity of the relevant activities monitored are presented and discussed.

7.2 Data Distribution

Reinforcing steel productivity data of the various activities observed were collected at the macro and micro-levels and were distributed as follows:

A. Macro-Level Observation

At the macro-level, a total of 1000 productivity data points were collected and distributed as follows:

1. Isolated foundations, 49 data points
2. Base slabs, i.e. raft foundations and ground slabs, 130 data points
3. Columns, 180 data points
4. Walls, 269 data points
5. Beams, 210 data points
6. Slab panels, 162 data points

B. Micro-Level Observation

At the micro-level, a total of 3432 data points were collected and distributed as follows:

1. Isolated foundations, 221 data points
2. Base slabs, 200 data points
3. Rectangular columns, 430 data points
4. Circular columns, 253 data points
5. Linear beams, 1143 data points
6. Curved beams, 169 data points
7. Rectangular slab panels, 673 data points
8. Non-rectangular slab panels, 343 data points

The characteristics of the observed projects are highlighted in table 6.1 previously presented in chapter six.

7.3 Gang Characteristics

Reinforcing steel gangs are not very different from formwork gangs. However, a noticeable difference between the two gangs is that a reinforcing steel gang does not have assistants amongst its members, all gang members are skilled labours. A typical observed steel fixer team consists, on average, of four to six fixers with field experience ranges from twelve to twenty years. The team members usually work in pairs, however, similar to the previously illustrated case in formwork, if the task involves fixing small quantity of reinforcement with relatively short bars, a single fixer performs the activity. As the case with formwork and concreting gangs, on all observed sites, reinforcing steel gangs were subcontracted and paid on a lump sum basis.

7.4 Analysis of Reinforcing Steel Fixing Labour Productivity

The effects and relative influence of buildability factors on reinforcing steel fixing labour productivity of the various activities and elements observed at both, macro and micro levels, were quantified using linear regression analysis. Regression coefficients previously presented in chapter five were quantified and the relative influence of these factors was determined using the standardisation technique. Such coefficients represent the unique impacts of the relevant buildability factors on labour productivity.

Activities monitored included fixing reinforcement in isolated foundations, base slabs, columns, walls, beams and slab panels. With the exception of the variability of isolated footing sizes, the impacts of all other hypothesised buildability factors on labour productivity are statistically significant at 0.050 significance level. In addition, the Variance Inflation Factors (VIF) amongst the variables are below the cut-off value of 10, indicating reasonable correlations and therefore reliable estimates of all quantified regression coefficients.

The influence of all buildability factors on labour productivity are in accordance with the hypothesised effects previously discussed in chapter three. Results of regression analyses of the various observed activities are presented.

7.4.1 Isolated Foundations

A. Macro-Level Observation

The variability of footing sizes, characteristic bar diameter and the total quantity of reinforcement fixed were hypothesised to influence the labour productivity of fixing reinforcing steel in isolated foundations. The relationship between these buildability factors and labour productivity is determined by the following multiple regression model:

$$P(kg/mh) = b_0 + b_1\,VOF + b_2\,CBDia + b_3\,TQ$$

Where VOF = total number of different footing sizes; CBDia = characteristic bar diameter as previously defined in chapter two; and TQ = total quantity of reinforcement fixed.

The overall regression model and coefficients statistics are presented in tables 7.1 and 7.2 respectively.

Table 7.1 Overall Regression Model Statistics for Macro-Level Reinforcing Steel Labour Productivity of Isolated Foundations

Correlation Coefficient (R)	*92.77%*
Coefficient of Determination (R^2)	*86.07%*
Standard Error	*21.72*
F(3,45)	*92.67*
p-value	*0.000*
No. of Observations	*49*

Table 7.2 Regression Coefficients Statistics for Macro-Level Reinforcing Steel Labour Productivity of Isolated Foundations

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
CBDia (mm)	*10.83*	*1.27*	*0.000*	*2.12*	*0.693*	*1*	*1.00*
TQ (kg)	*0.00460*	*0.00122*	*0.000*	*2.19*	*0.308*	*2*	*0.44*
VOF	*-0.652*	*0.830*	*0.436*	*1.12*	*-0.0463*	*N/A*[1]	*N/A*

[1]Influence rank and relative influence of only significant buildability factors, i.e. p-value < 0.050, on labour productivity were quantified.

The relationship between steel fixing labour productivity of isolated foundations and the relevant buildability factors at the macro-level is determined by the following multiple regression model:

$$P\,(kg\,/\,mh) = -93.64 + 10.83\,CBDia + 0.00460TQ - 0.652\,VOF \qquad \ldots 7.1$$

B. Micro-Level Observation

The independent buildability factors hypothesised to have an influence at this level are the characteristic bar diameter and the quantity of reinforcement fixed in the observed footing.

The relationship between labour productivity and these buildability factors is determined by the following simple regression model:

$$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,Q$$

The overall regression model and coefficients statistics are presented in tables 7.3 and 7.4 respectively.

Table 7.3 Overall Regression Model Statistics for Micro-Level Reinforcing Steel Labour Productivity of Isolated Foundations

Correlation Coefficient (R)	*94.65*
Coefficient of Determination (R^2)	*89.58*
Standard Error	*28.42*
F(2,218)	*937.54*
p-value	*0.000*
No. of Observations	*221*

Table 7.4 Regression Coefficients Statistics for Micro-Level Reinforcing Steel Labour Productivity of Isolated Foundations

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
Ch.B.Dia (mm)	*16.15*	*0.644*	*0.000*	*1.75*[1]	*0.726*	*1*	*1.00*
Q (kg)	*0.0952*	*0.00932*	*0.000*		*0.296*	*2*	*0.41*

[1]Variance inflation factor indicating the correlation between the characteristic bar diameter and quantity of reinforcement in the model.

The relationship between labour productivity and design variables shown in table 7.4 shown above is therefore quantified by the following regression model:

$$P(kg/mh) = -147.74 + 16.15\,CBDia + 0.0952\,Q \qquad \ldots 7.2$$

7.4.2 Base and Suspended Flat Slabs

The labour productivities of fixing reinforcement in raft foundations, ground and suspended flat slabs were observed at both levels; macro and micro. Macro-level observation included monitoring the total productive input used to fix the total quantity of reinforcement, i.e. bottom and top layers, whereas, micro-level observation was limited to collecting the productive input applied to fix the reinforcement of each layer separately. The objective of such an observation was to quantify the average difference in labour productivity between fixing the top and bottom layers of reinforcing steel bars. The fixing process of reinforcement in base slabs, i.e. raft foundations and ground slabs, as well as suspended flat slabs is identical; consequently, the impacts of the buildability factors on their labour productivities were quantified collectively.

A. Macro-Level Observation

Buildability factors hypothesised to influence the reinforcing steel fixing labour productivity of this activity are: the characteristic bar diameter; total quantity of reinforcement fixed and the geometry of the slab. Moreover, a different relationship between labour productivity and the total quantity of reinforcement for the two categories of slab geometry, i.e. rectangular versus non-rectangular, was hypothesised, and an interaction term between the two variables was added to the model shown in equation 7.3 below to verify this hypothesis.

The relationship between labour productivity and the buildability factors is quantified by the following interaction-regression model:

$$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,TQ + b_3\,Geom + b_4\,(Geom * TQ) \qquad \ldots 7.3$$

Where CBDia = characteristic bar diameter; TQ = total quantity of reinforcement fixed in both layers; Geom = a dummy variable which indicates the geometry of the observed slab and quantifies the average difference in fixing labour productivity between non-rectangular and rectangular slabs. It assumes the value of 0 if the slab is rectangular, and 1 if non-rectangular; and (Geom * TQ) = an interaction term which quantifies the average difference in the slope of the relationship between labour productivity and total quantity of reinforcement fixed for the two categories of slab geometry.

The overall regression model and coefficients are shown in tables 7.5 and 7.6 respectively.

Table 7.5 Overall Regression Model Statistics for Macro-Level Reinforcing Steel Labour Productivity of Base and Suspended Flat Slabs

Correlation Coefficient (R)	*91.09%*
Coefficient of Determination (R^2)	*82.97%*
Standard Error	*21.48*
F(4,125)	*152.25*
p-value	*0.000*
No. of Observations	*130*

Table 7.6 Regression Coefficients Statistics for Macro-Level Reinforcing Steel Labour Productivity of Base and Suspended Flat Slabs

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
CBDia (mm)	*7.43*	*0.556*	*0.000*	*1.77*	*0.656*	*1*	*1.00*
TQ (kg)	*0.000492*	*0.000*	*0.000*	*1.52*	*0.241*	*2*	*0.37*
Geom	*-20.78*	*5.56*	*0.000*	*1.99*	*N/A*[1]	*N/A*	*N/A*
*(Geom * TQ)*	*0.000761*	*0.000*	*0.00201*	*2.06*	*N/A*	*N/A*	*N/A*

[1]Dummy variables are used to quantify differences in levels between or amongst categories, therefore, the normal interpretation for standardised coefficients does not apply.

The relationship between reinforcing steel fixing labour productivity and the relevant buildability factors is determined by the following multiple regression model:

$$\begin{aligned} P(kg/mh) = {} & 51.72 + 7.43\,CBDia + 0.000492\,TQ - 20.78\,Geom \\ & + 0.000761(Geom * TQ) \end{aligned} \qquad \ldots 7.4$$

The dummy variable representing the average difference in labour productivity between fixing reinforcement in non-rectangular and rectangular slabs quantifies an average loss in labour productivity of 20.78 kg/mh associated with fixing reinforcement in non-rectangular slabs.

The coefficient of the interaction term between the total quantity of reinforcement fixed and slab geometry, reveals a significant increase in the slope of the relationship between the total quantity of reinforcement fixed and labour productivity between non-rectangular and rectangular slabs, holding the characteristic bar diameter constant. This finding may be attributed to two factors: a) as the quantity of reinforcement increases in non-rectangular slabs, less variability of bar lengths is encountered by steel fixers, therefore, higher labour productivity is achieved; and b) that the influence of reinforcement quantity is stronger than the impact of shape geometry on labour productivity.

Table 7.7 Average Values of Buildability Factors Influencing Macro-Level Reinforcing Steel Labour Productivity of Base and Suspended Flat Slabs

Geometry of Slab	*Average Characteristic Bar Diameter (mm)*	*Average Total Quantity of Reinforcement Fixed (kg)*
Rectangular	*15.29*	*18192.33*
Non-rectangular	*13.39*	*14164.13*
Total	*14.62*	*16766.97*

The average difference in labour productivity between non-rectangular and rectangular slabs is quantified by substituting the average values of the corresponding buildability factors shown in table 7.7 above into equation 7.4 as follows:

1. Non-rectangular Slabs, Geom = 1:

$$
\begin{gathered}
P(kg/mh) = 51.72 + 7.43(13.39) + 0.000492(14164.13) - 20.78(1) \\
+ 0.000761(1 * 14164.13) = 148.18
\end{gathered}
$$

2. Rectangular Slabs, Geom = 0:

$$P(kg/mh) = 51.72 + 7.43(15.29) + 0.000492(18192.33) - 20.78(0) + 0.000761(0 * 18192.33) = 174.28$$

Hence, the average difference in labour productivity between non-rectangular and rectangular slabs is determined as shown below:

$$\left[\frac{(174.28 - 148.18)}{174.28}\right] * 100 = 14.98\% \qquad \ldots 7.5$$

Thus, compared with rectangular slabs, an average loss in labour productivity of 15% is associated with fixing reinforcement in non-rectangular slabs.

B. Micro-Level Observation

As was previously indicated, the objective of this observation was to quantify the average difference in labour productivity of fixing reinforcing steel bars between top and bottom layers. At this level of observation, the productive labour input of fixing reinforcement in each reinforcement layer was collected separately, and the labour productivity of fixing reinforcing steel bars in each layer was quantified based on the quantity of reinforcement placed in the relevant layer and its associated input. Buildability factors hypothesised to influence the labour productivity at this level are the characteristic bar diameter, quantity of reinforcement fixed in the observed layer, geometry of observed slab and the observed layer location, i.e. bottom or top.

The relationship between labour productivity and the buildability factors is quantified by the following interaction-regression model:

$$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,Q + b_3\,Geom + b_4\,(Geom * Q) + b_5\,LLoc$$

Where CBDia, Q and Geom are, as previously defined, the characteristic bar diameter, quantity of reinforcement fixed in the observed layer, and Geom is a dummy variable which indicates the geometry of the observed slab and quantifies the average difference in fixing labour productivity between non-rectangular and rectangular slabs. It assumes the value of 0 if the slab is rectangular, and 1 if non-rectangular. The influence on labour productivity due to layer location is quantified using a different dummy variable in the model termed LLoc, which assumes the value of 0 if the monitored layer is at the bottom level of the slab, and 1 if at the top.

The overall regression model and coefficients statistics are shown in tables 7.8 and 7.9 respectively.

Table 7.8 Overall Regression Model Statistics for Micro-Level Reinforcing Steel Labour Productivity of Base and Suspended Flat Slabs

Correlation Coefficient (R)	*89.71%*
Coefficient of Determination (R^2)	*80.49%*
Standard Error	*25.96*
F(5,194)	*160.04*
p-value	*0.000*
No. of Observations	*200*

Table 7.9 Regression Coefficients Statistics for Statistics for Micro-Level Reinforcing Steel Labour Productivity of Base and Suspended Flat Slabs

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
CBDia (mm)	*8.71*	*0.619*	*0.000*	*2.06*	*0.641*	*1*	*1.00*
Q (kg)	*0.000871*	*0.000173*	*0.000*	*1.71*	*0.209*	*2*	*0.33*
Geom	*-27.26*	*5.37*	*0.000*	*2.05*	*N/A*	*N/A*	*N/A*
*(Geom * Q)*	*0.00157*	*0.000452*	*0.000*	*2.34*	*N/A*	*N/A*	*N/A*
LLoc	*-37.28*	*3.73*	*0.000*	*1.02*	*N/A*	*N/A*	*N/A*

The relationship between reinforcing steel labour productivity and the relevant buildability factors is quantified by the following multiple regression model:

$$\begin{aligned} P\,(kg/mh) = {} & 57.55 + 8.71\,CBDia + 0.000871\,Q - 27.26\,Geom \\ & + 0.00157\,(Geom * Q) - 37.28\,LLoc \end{aligned} \quad \ldots 7.6$$

The dummy variable representing the average difference in labour productivity between fixing reinforcement in non-rectangular and rectangular slabs indicates an overall average loss in labour productivity of 27.26 kg/mh associated with fixing reinforcement in non-rectangular slabs. The coefficient of the interaction term between the quantity of reinforcement fixed in the relevant monitored layer and slab geometry, indicates, once again, a significant increase in the slope of the relationship between the quantity of reinforcement fixed and labour productivity between non-rectangular and rectangular slabs, holding the characteristic bar diameter and layer location constant. Moreover, and relative to the bottom layer, the regression coefficient of the layer location dummy variable quantifies an overall average loss of 37.28 kg/mh in labour productivity associated with fixing top layer reinforcing bars, holding all other variables in the model constant.

Table 7.10-a Average Values of Buildability Factors Influencing Micro-Level Reinforcing Steel Labour Productivity of Rectangular Base and Suspended Flat Slabs

Layer Location	***Average Characteristic Bar Diameter (mm)***	***Average Total Quantity of Reinforcement Fixed (kg)***
Bottom	*13.95*	*9380.42*
Top	*14.82*	*10942.69*
Total	*14.35*	*10090.55*

Table 7.10-b Average Values of Buildability Factors Influencing Micro-Level Reinforcing Steel Labour Productivity of Non-Rectangular Base and Suspended Flat Slabs

Layer Location	***Average Characteristic Bar Diameter (mm)***	***Average Total Quantity of Reinforcement Fixed (kg)***
Bottom	*13.39*	*7454.35*
Top	*14.73*	*9353.03*
Total	*13.95*	*8247.47*

To quantify the average difference in labour productivity between fixing reinforcing steel bars in top and bottom layers, the average values of the corresponding buildability factors shown in tables 7.10-a & b are substituted into equation 7.6 for the relevant category of slab geometry as follows:

1. Quantifying Average Percentage Difference in Labour Productivity between Top and Bottom Reinforcement layers in Rectangular Slabs

The average difference in labour productivities between top and bottom layers fixed in rectangular slabs, i.e. Geom = 0, is quantified as follows:

a) Top Layer, LLoc = 1:

$$P(kg/mh) = 57.55 + 8.71(14.82) + 0.000871(10942.69) - 27.26(0) \\ + 0.00157(0*10942.69) - 37.28(1) = 158.88$$

b) Bottom Layer, LLoc = 0:

$$P(kg/mh) = 57.55 + 8.71(13.95) + 0.000871(9380.42) - 27.26(0) \\ + 0.00157(0*9380.42) - 37.28(0) = 187.22$$

Therefore, the average percentage difference in fixing labour productivity between top and bottom reinforcement layers in rectangular slabs is determined as shown below:

$$\left[\frac{(187.22 - 158.88)}{187.22}\right] * 100 = 15.14\% \qquad \text{... 7.7}$$

Hence, an average loss in labour productivity of 15%, compared with the bottom layer, is estimated for fixing top layer reinforcing steel bars in rectangular slabs.

2. Quantifying Average Percentage Difference in Labour Productivity between Top and Bottom Reinforcement layers in Non-rectangular Slabs

The average difference in labour productivities between top and bottom layers fixed in non-rectangular slabs, i.e. Geom = 1, is quantified as follows:

a) Top Layer, LLoc = 1:

$$P(kg/mh) = 57.55 + 8.71(14.73) + 0.000871(9353.03) - 27.26(1) \\ + 0.00157(1*9353.03) - 37.28(1) = 144.14$$

b) Bottom Layer, LLoc = 0:

$$P(kg/mh) = 57.55 + 8.71(13.39) + 0.000871(7454.35) - 27.26(1)$$
$$+ 0.00157(1 * 7454.35) - 37.28(0) = 165.11$$

Thus, the average percentage difference in fixing labour productivity between top and bottom reinforcement layers in non-rectangular slabs is quantified as shown below:

$$\left[\frac{(165.11 - 144.14)}{165.11}\right] * 100 = 12.70\% \qquad \ldots 7.8$$

Hence, an average loss in labour productivity of about 13%, compared with the bottom layer, is estimated for fixing top layer reinforcing steel bars in non-rectangular slabs.

A quantified minor difference of approximately 2% between the results obtained for the two categories of slab geometry indicating almost a consistency in the average difference in labour productivity of fixing top and bottom layers reinforcement.

7.4.3 Columns

A. Macro-Level Observation

The major buildability factors hypothesised to influence reinforcing steel labour productivity of columns are the variability of column sizes, characteristic bar diameter, total quantity of reinforcement fixed and the percentage of reinforcement fixed in circular columns.

The relationship between labour productivity and these factors is quantified by the following multiple linear regression model:

$$P(Kg/mh) = b_0 + b_1\,VOC + b_2\,CBDia + b_3\,TQ + b_4\,PSCC$$

Where VOC = total number of different column sizes; CBDia = the characteristic bar diameter as previously defined; TQ = total quantity of reinforcement including links fixed in columns; and PSCC = percentage of steel fixed in circular columns, and is quantified as shown below:

$$PSCC = \frac{\textbf{Total quantity of reinforcement fixed in circular columns (kg)}}{\textbf{Total quantity of reinforcement fixed in all columns (kg)}} * 100$$

The overall regression model and coefficients statistics are shown in tables 7.11 and 7.12 respectively.

Table 7.11 Overall Regression Model Statistics for Macro-Level Reinforcing Steel Labour Productivity of Columns

Correlation Coefficient (R)	*93.76%*
Coefficient of Determination (R^2)	*87.91%*
Standard Error	*9.09*
F(4,175)	*318.05*
p-value	*0.000*
No. of Observations	*180*

Table 7.12 Regression Coefficients Statistics for Macro-Level Reinforcing Steel Labour Productivity of Columns

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
VOC	*-0.638*	*0.206*	*0.0020*	*1.17*	*-0.0880*	*4*	*0.10*
CBDia (mm)	*6.76*	*0.247*	*0.000*	*1.38*	*0.846*	*1*	*1.00*
TQ (kg)	*0.000635*	*0.000211*	*0.00300*	*1.47*	*0.0958*	*3*	*0.11*
PSCC	*-0.289*	*0.0279*	*0.000*	*1.09*	*-0.285*	*2*	*0.34*

The overall multiple regression model quantifying the relationship between reinforcing steel labour productivity of columns and the relevant buildability factors at the macro-level is shown below:

$$P(Kg/mh) = -47.97 - 0.638\,VOC + 6.76\,CBDia + 0.000635\,TQ - 0.289\,PSCC \quad \ldots 7.9$$

B. Micro-Level Observation

At this level, the major buildability factors hypothesised to impact the labour productivity are the characteristic bar diameter, quantity of reinforcement fixed and the geometry of the observed column, i.e. rectangular versus circular. In addition, a different impact of reinforcement quantity on labour productivity was hypothesised between circular and rectangular columns. The logic behind such a hypothesis stems from the difference in the fixing process between the two categories of column geometry as was previously illustrated in chapter three.

The relationship between labour productivity and these variables at the micro-level is quantified by the following interaction regression model:

$$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,Q + b_3\,CGeom + b_4\,(CGeom * Q)$$

Where CBDia and Q, as previously defined, are the characteristic bar diameter and reinforcement quantity fixed in the observed column respectively. In addition, CGeom is a dummy variable which indicates the geometry of the observed column and quantifies the average difference in labour productivity between the two categories of columns. The value of 0 is selected to represent rectangular columns whereas the value of 1 is used for circular columns.

The overall regression model and coefficients statistics are shown in tables 7.13 and 7.14 respectively.

Table 7.13 Overall Regression Model Statistics for Micro-Level Reinforcing Steel Labour Productivity of Columns

Correlation Coefficient (R)	*90.69%*
Coefficient of Determination (R^2)	*82.24%*
Standard Error	*14.61*
$F(4,678)$	*785.15*
p-value	*0.000*
No. of Observations	*683*

Table 7.14 Regression Coefficients Statistics for Micro-Level Reinforcing Steel Labour Productivity of Columns

Coefficient	*Value*	*Standard Error*	*p-value*	*VIF*	*Standardised Coefficient Value*	*Influence Rank*	*Relative Influence*
CBDia (mm)	*4.98*	*0.310*	*0.000*	*4.02*	*0.522*	*1*	*1.00*
Q (kg)	*0.114*	*0.0890*	*0.000*	*3.82*	*0.405*	*2*	*0.78*
CGeom	*-13.32*	*2.12*	*0.000*	*3.34*	*N/A*	*N/A*	*N/A*
*(CGeom * Q)*	*-0.159*	*0.0103*	*0.000*	*4.00*	*N/A*	*N/A*	*N/A*

The relationship between reinforcing steel labour productivity of columns and the relevant buildability factors at the micro-level is determined by the following multiple regression model:

$$\boldsymbol{P(kg\,/\,mh) = -5.76 + 4.98\,CBDia + 0.114\,Q - 13.32\,CGeom - 0.159(CGeom * Q)} \quad \ldots 7.10$$

In accordance with the hypothesised loss in labour productivity of fixing circular columns reinforcement, an overall average loss of 13.32 kg/mh, compared to rectangular columns, is associated with fixing reinforcement in circular columns.

The regression coefficient of the interaction term shown in equation 7.10 quantifies a reduction in the intensity of the influence of reinforcement quantity on labour productivity of circular columns. This finding is expected due to the additional labour input required to uniformly and symmetrically distribute longitudinal reinforcing bars around the perimeters of circular columns.

To quantify the average percentage difference in labour productivity between circular and rectangular columns, the average values of characteristic bar diameter and quantity of reinforcement fixed in the relevant category of column geometry shown in table 7.15 below, are substituted into equation 7.10 as follows:

Table 7.15 Average Characteristic Bar Diameter and Quantity of Reinforcement Fixed in Rectangular and Circular Observed Columns

Column Geometry	*Average Characteristic Bar Diameter (mm)*	*Average Quantity of Reinforcement (kg)*
Rectangular	*18.36*	*170.29*
Circular	*19.36*	*178.30*
Total	*18.73*	*173.26*

1. Circular Columns, CGeom = 1:

$$P(kg/mh) = -5.76 + 4.98(19.36) + 0.114(178.30) \\ -13.32(1) - 0.159(1*178.30) = 69.31$$

2. Rectangular Columns, CGeom = 0:

$$P(kg/mh) = -5.76 + 4.98(18.36) + 0.114(170.29) \\ -13.32(0) - 0.159(0*170.30) = 105.09$$

The average percentage difference in reinforcing steel productivity between circular and rectangular columns is therefore quantified as follows:

$$\left[\frac{(105.09 - 69.31)}{105.09}\right] * 100 = 34.05\% \qquad \text{...7.11}$$

Hence, in comparison with rectangular columns, an average loss in labour productivity of 34% is associated with fixing reinforcement in circular columns.

Since the interaction regression model involves a single dummy variable, the overall average loss of both categories of column geometry is quantified by substituting the average values of characteristic bar diameter as well as the quantity of reinforcement fixed in the observed columns shown in table 7.15 into equation 7.10 as follows:

a) Circular Columns, CGeom = 1:

$$P(kg/mh) = -5.76 + 4.98(18.73) + 0.114(173.26) \\ -13.32(1) - 0.159(1*173.26) = 66.40$$

b) Rectangular Columns, CGeom = 0:

$$P(kg/mh) = -5.76 + 4.98(18.73) + 0.114(173.26) \\ -13.32(0) - 0.159(0*173.26) = 107.27$$

Therefore, the overall average percentage difference in reinforcing steel productivity between circular and rectangular columns is therefore quantified as shown below:

$$\left[\frac{(107.27-66.40)}{107.27}\right]*100=38.10\% \qquad ...7.12$$

Thus, in comparison with rectangular columns, an overall average loss in labour productivity of 38% is associated with fixing reinforcement in circular columns.

7.4.4 Walls

The major buildability factors hypothesised to influence the labour productivity of this activity are the characteristic bar diameter, total quantity of reinforcement fixed and wall thickness.

The relationship between labour productivity and these factors is quantified by the following multiple regression model:

$$P(kg/mh)=b_0+b_1\,CBDia+b_2\,TQ+b_3\,T$$

Where CBDia, TQ and T represent the characteristic bar diameter, total quantity of reinforcement fixed and wall thickness respectively.

The overall regression model and coefficients statistics are shown in tables 7.16 and 7.17 respectively.

Table 7.16 Overall Regression Model Statistics for Reinforcing Steel Labour Productivity of Walls

Correlation Coefficient (R)	*85.60%*
Coefficient of Determination (R^2)	*73.26%*
Standard Error	*22.40*
F(3,265)	*242.07*
p-value	*0.000*
No. of Observations	*269*

Table 7.17 Regression Coefficients Statistics for Reinforcing Steel Labour Productivity of Walls

Coefficient	*Value*	*Standard Error*	*p-value*	*VIF*	*Standardised Coefficient Value*	*Influence Rank*	*Relative Influence*
CBDia (mm)	*2.02*	*0.554*	*0.000*	*1.73*	*0.152*	*3*	*0.26*
TQ (kg)	*0.00366*	*0.000230*	*0.000*	*1.30*	*0.579*	*1*	*1.00*
T (mm)	*0.411*	*0.0590*	*0.000*	*1.81*	*0.298*	*2*	*0.51*

The relationship between reinforcing steel labour productivity of walls and the relevant buildability factors is determined by the following multiple regression model:

$$P(kg/mh) = -15.98 + 2.02\,CBDia + 0.00366\,TQ + 0.411\,T \qquad ...7.13$$

7.4.5 Beams

A. Macro-Level Observation

At this level of observation, the major investigated buildability factors included the variability of beam sizes, characteristic bar diameters of main longitudinal bars and stirrups, total quantity of reinforcement fixed including stirrups, average width and depth of beams and the percentage of reinforcement fixed in curved beams.

The relationship between labour productivity and the buildability factors is quantified by the following multiple regression model:

$$P(kg/mh) = b_0 + b_1\,VOB + b_2\,CBDia + b_3\,CSDia + b_4\,TQ + b_5\,AW + b_6\,AD + b_7\,PRCB$$

Where VOB = total number of different beam sizes; CBDia = the characteristic longitudinal bar diameter; CSDia = a dummy variable which represents the characteristic stirrup diameter and quantifies the average difference in labour productivity between fixing 8 mm and 10 mm in diameter stirrups. It assumes the value of 0 if an 8 mm in diameter stirrup was fixed, and 1 if 10 mm; TQ = total quantity of reinforcement fixed in beams; AW = average width of beams; AD = average depth of beams; and PRCS = percentage of reinforcement fixed in curved beams quantified as follows:

$$\frac{\textbf{Total quantity of reinforcement fixed in curved beams (kg)}}{\textbf{Total quantity of reinforcement fixed in all beams in floor (kg)}} * 100$$

The overall regression model and coefficients statistics are shown in tables 7.18 and 7.19 respectively.

Table 7.18 Overall Regression Model Statistics for Macro-Level Reinforcing Steel Labour Productivity of Beams

Correlation Coefficient (R)	*88.24%*
Coefficient of Determination (R^2)	*77.86%*
Standard Error	*11.36*
F(7,202)	*101.45*
p-value	*0.000*
No. of Observations	*210*

Table 7.19 Regression Coefficients Statistics for Macro-Level Reinforcing Steel Labour Productivity of Beams

Coefficient	Value	Standard Error	p-value	VIF	Standardised Coefficient Value	Influence Rank	Relative Influence
VOB	-0.341	0.0922	0.000	2.23	-0.183	4	0.26
CBDia (mm)	6.70	0.375	0.000	1.39	0.696	1	1.00
CSDia (mm)	-7.47	1.89	0.000	1.15	N/A	N/A	N/A
TQ (kg)	0.00108	0.000	0.000	1.82	0.551	2	0.79
AW (mm)	-0.0363	0.126	0.00436	1.38	-0.112	6	0.16
AD (mm)	-0.0500	0.0810	0.000	1.11	-0.214	3	0.31
PRCB	-0.391	0.103	0.000	1.03	-0.128	5	0.18

The relationship between fixing labour productivity of beams observed at the macro-level and the relevant buildability factors is determined by the following multiple regression model:

$$\begin{aligned} P(kg/mh) = & -6.15 - 0.341\,VOB + 6.70\,CBDia - 7.47\,CSDia + 0.00108\,TQ \\ & - 0.0363\,AW - 0.0500\,AD - 0.391\,PRCB \end{aligned} \qquad \ldots 7.14$$

Since only two values of stirrup diameters fixed in beams, 8 mm and 10 mm, were encountered on all monitored sites, the influence of stirrups diameter is quantified using a dummy variable having the following two values: 0 if an 8 mm in diameter stirrup is fixed, and 1 if 10 mm. The regression coefficient value of the dummy variable shown in table 7.19, quantifies the average difference in labour productivity between the two specified diameters. The average difference in labour productivity between fixing 10 mm and 8 mm stirrups is 7.47 kg/mh. The negative sign of the coefficient indicates that the labour productivity associated with fixing 10 mm stirrups in beams is, on average, lower than that of fixing 8 mm stirrups. The average percentage loss in labour productivity due to fixing 10 mm rather than 8 mm in diameter stirrups is quantified by substituting the average values of buildability factors shown in table 7.20 below into equation 7.14 for the two categories of the dummy variables, i.e. 0 and 1, as follows:

Table 7.20 Average Values of Buildability Factors Influencing Macro-Level Reinforcing Steel Labour Productivity of Beams

Independent Design Variable	*Average Value*
VOB	*13.25*
CBDia (mm)	*17.69*
TQ (kg)	*7070.19*
AW (mm)	*254.24*
AD (mm)	*595.19*
PRCB	*2.33*

1. **Fixing 10 mm Diameter Stirrups, CSDia = 1:**

$$\begin{aligned} P(kg/mh) = & -6.15 - 0.341(13.25) + 6.70(17.69) - 7.47(1) \\ & + 0.00108(7070.19) - 0.0363(254.24) \\ & - 0.0500(595.19) - 0.391(2.33) = 68.12 \end{aligned}$$

2. **Fixing 8 mm Diameter Stirrups, CSDia = 0:**

$$\begin{aligned} P(kg/mh) = & -6.15 - 0.341(13.25) + 6.70(17.69) - 7.47(0) \\ & + 0.00108(7070.19) - 0.0363(254.24) \\ & - 0.0500(595.19) - 0.391(2.33) = 75.59 \end{aligned}$$

Thus, the average percentage loss in labour productivity due to specifying 10 mm instead of 8 mm in diameter stirrup is quantified as follows:

$$\left[\frac{(75.59-68.12)}{75.59}\right]*100 = 9.90\% \qquad ...7.15$$

Therefore, and holding all other variables in the model constant, fixing 10 mm stirrups, compared with 8 mm in diameter, yields, on average, approximately 10% loss in reinforcing steel fixing labour productivity of beams.

B. Micro-Level Observation

Since the direct fixing activity of selected beams was observed, the overall effect of the variability of beam sizes has no effect on labour productivity at the micro-level. The major design buildability factors hypothesised to influence the reinforcing steel labour productivity are the characteristic bar diameter, stirrups diameter, quantity of reinforcement fixed including stirrups, width and depth of beams, and the geometry of beams, i.e. linear versus curved. In addition, as was previously discussed in chapter three, reinforcement fixing process is different between linear and curved beams. Therefore, we hypothesise that the relationship between the depth of beams and labour productivity to be different between linear and curved beams. In order to investigate this hypothesis, an interaction term between the two variables was incorporated into the regression model as shown in equation 7.16 below.

The relationship between reinforcing steel labour productivity and these factors is quantified by the following multiple interaction-regression model:

$$\begin{aligned} P(kg/mh) = b_0 &+ b_1\,CBDia + b_2\,SDia + b_3\,Q + b_4\,W + b_5\,D \\ &+ b_6\,GOS + b_7\,(GOS*D) \end{aligned} \qquad ...7.16$$

Where CBDia = the characteristic bar diameter; SDia = stirrups bar diameter; Q = quantity of reinforcement fixed in the observed beam including stirrups; W = width of beam; D = depth of beam; and GOS = a dummy variable which indicates the geometry of beam span and quantifies the average difference in labour productivity between fixing reinforcement in curved and linear beams. The span geometry dummy variable assumes the following two values: 0 if beam is linear in span, and 1 if curved.

The overall regression model and coefficients statistics are shown in tables 7.21 and 7.22 respectively.

Table 7.21 Overall Regression Model Statistics for Micro-Level Reinforcing Steel Labour Productivity of Beams

Correlation Coefficient (R)	*88.16%*
Coefficient of Determination (R^2)	*77.71%*
Standard Error	*16.25*
F(7,1304)	*649.57*
p-value	*0.000*
No. of Observations	*1312*

Table 7.22 Regression Coefficients Statistics for Micro-Level Reinforcing Steel Labour Productivity of Beams

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
CBDia (mm)	*6.23*	*0.195*	*0.000*	*2.28*	*0.630*	*1*	*1.00*
SDia (mm)	*-2.65*	*1.05*	*0.0121*	*1.37*	*N/A*	*N/A*	*N/A*
Q (kg)	*0.0286*	*0.00119*	*0.000*	*1.95*	*0.438*	*2*	*0.70*
W (mm)	*-0.0515*	*0.0468*	*0.000*	*1.84*	*-0.195*	*3*	*0.31*
D (mm)	*-0.00832*	*0.0266*	*0.00180*	*1.67*	*-0.0530*	*4*	*0.0841*
GOS	*-14.67*	*4.23*	*0.000*	*9.95*	*N/A*	*N/A*	*N/A*
*(GOS * D)*	*-0.0206*	*0.00620*	*0.000*	*10.26*	*N/A*	*N/A*	*N/A*

The interaction regression model quantifying the relationship between reinforcing steel fixing labour productivity and buildability factors is determined by the following regression model:

$$\begin{aligned} P(kg/mh) = {} & 5.78 + 6.23\,CBDia - 2.65\,SDia + 0.0286\,Q - 0.0515\,W - 0.00832\,D \\ & - 14.67\,GOS - 0.0206\,(GOS * D) \end{aligned} \qquad \ldots 7.17$$

According to the quantified regression model shown in equation 7.17, an average loss in labour productivity of 14.67 kg/mh is associated with fixing reinforcement in curved beams. In addition, and in accordance with the hypothesised interaction effect between beam depth and span geometry, the coefficient of the interaction term in the model indicates a significant reduction in the slope of the relationship between the depth of beams and the labour productivity for the two categories of the span geometry. In comparison with linear beams, the negative impact of beam depth on labour productivity is stronger in curved beams.

The major objective of conducting such an investigation at the micro-level is to quantify the average percentage difference in labour productivity between fixing reinforcement in curved and linear beams. In order to achieve this objective, the average values of buildability factors shown in table 7.23 are substituted into equation 7.17 for the relevant span geometry as follows:

Table 7.23 Average Values of Buildability Factors Influencing Micro-Level Reinforcing Steel Labour Productivity of Observed Linear and Curved Beams

Span Geometry	*Average Characteristic Diameter (mm)*	*Average Quantity of Reinforcement Fixed (Kg)*	*Average Width (mm)*	*Average Depth (mm)*
Linear	*18.34*	*316.85*	*286.80*	*618.80*
Curved	*16.62*	*151.09*	*231.70*	*652.10*
Total	*18.11*	*295.31*	*279.84*	*623.36*

1. Quantifying Average Percentage Difference in Labour Productivity due to Span Geometry for 8 mm Stirrups in Diameter, SDia = 0:

The average reinforcing steel fixing labour productivities of curved and linear beams respectively for 8 mm in diameter stirrups are quantified as follows:

$$P(kg/mh) = 5.78 + 6.23(16.62) - 2.65(0) + 0.0286(151.09) - 0.0515(231.70) - 0.00832(652.10) \\ - 14.67(1) - 0.0206(1 * 652.10) = 68.18$$

$$P(kg/mh) = 5.78 + 6.23(18.34) - 2.65(0) + 0.0286(316.85) - 0.0515(286.80) - 0.00832(618.80) - 14.67(0) - 0.0206(0*618.80) = 109.18$$

Hence, the average percentage difference in reinforcing steel fixing labour productivity between curved and linear beams for 8 mm in diameter stirrups is determined as shown below:

$$\left[\frac{(109.18-68.18)}{109.18}\right]*100 = 37.55\% \qquad ...7.18$$

Thus, in comparison with linear beams, an average loss of approximately 38% in labour productivity is associated with fixing reinforcement in curved beams.

2. Quantifying Average Percentage Difference in Labour Productivity due to Span Geometry for 10 mm Stirrups in Diameter, SDia = 1:

The average reinforcing steel fixing labour productivities of curved and linear beams respectively for 10 mm in diameter stirrups are determined as shown below:

$$P(kg/mh) = 5.78 + 6.23(16.62) - 2.65(1) + 0.0286(151.09) - 0.0515(231.70) - 0.00832(652.10) - 14.67(1) - 0.0206(1*652.10) = 65.53$$

$$P(kg/mh) = 5.78 + 6.23(18.34) - 2.65(1) + 0.0286(316.85) - 0.0515(286.80) - 0.00832(618.80) - 14.67(0) - 0.0206(0*618.80) = 106.53$$

Thus, the average percentage difference in reinforcing steel fixing labour productivity between curved and linear beams for 10 mm in diameter stirrups is quantified as shown below:

$$\left[\frac{(106.53-65.53)}{106.53}\right]*100 = 38.48\% \qquad ...7.19$$

Therefore, in comparison with linear beams, an average loss of approximately 38% in labour productivity is associated with fixing reinforcement in curved beams.

It can be seen from equations 7.18 and 7.19 the consistency in the obtained results. The quantified average percentage differences in reinforcing steel labour productivity between curved and linear beams for fixing 8 mm and 10 mm in diameter stirrups, apart from the round-off error, are almost identical.

In comparison with the macro-level results shown in table 7.19, we realise a shift in the relative influence on labour productivity between the depth and width of beams. Whilst the depth of beams is more influential than the width at the macro-level observation of this activity, results obtained from the micro-level observation indicates an opposite relative influence as shown in table 7.22. After careful consideration for the reason(s) behind this shift of the relative influence between the two variables, the researcher was unable to provide a reasonable explanation.

7.4.6 Slab Panels

A. Macro-Level Observation

The major buildability factors hypothesised to influence reinforcing steel fixing labour productivity of slab panels are the average panel area, characteristic bar diameter, total quantity of reinforcement fixed and the percentage of reinforcement fixed in non-rectangular panels.

The relationship between reinforcing steel fixing labour productivity and these factors is quantified by the following multiple regression model:

$$P(kg/mh) = b_0 + b_1\,AVA + b_2\,CBDia + b_3\,TQ + b_4\,PSNP$$

Where AVA = average panel area; CBDia = the characteristic bar diameter; TQ = total quantity of reinforcement fixed in slab panels; and PSNP = percentage of reinforcement fixed in non-rectangular slab panels. Average panel area and the percentage of reinforcement fixed in non-rectangular slab panels are quantified by the following expressions:

$$AVA = \frac{\textit{Total area of slab panels in floor } (m^2)}{\textit{Total number of slab panels in floor}}$$

$$PSNP = \frac{\textit{Total quantity of reinforcement fixed in non - rectangular slab panels (kg)}}{\textit{Total quantity of reinforcement fixed in all slab panels (kg)}} * 100$$

The overall regression model and coefficients statistics are shown in tables 7.24 and 7.25 respectively.

Table 7.24 Overall Regression Model Statistics for Macro-Level Reinforcing Steel Labour Productivity of Slab Panels

Correlation Coefficient (R)	*89.50%*
Coefficient of Determination (R^2)	*80.10%*
Standard Error	*12.40*
F(4,157)	*158.00*
p-value	*0.000*
No. of Observations	*162*

Table 7.25 Regression Coefficients Statistics for Macro-Level Reinforcing Steel Labour Productivity of Slab Panels

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
AVA (m^2)	*0.0594*	*0.0204*	*0.00418*	*1.17*	*0.112*	*4*	*0.16*
CBDia (mm)	*11.79*	*0.651*	*0.000*	*1.17*	*0.696*	*1*	*1.00*
TQ (kg)	*0.000953*	*0.000194*	*0.000*	*1.31*	*0.200*	*3*	*0.29*
PSNP	*-0.484*	*0.0342*	*0.000*	*1.03*	*-0.511*	*2*	*0.73*

The relationship between reinforcing steel labour productivity of slab panels observed at the macro-level and the relevant buildability factors is quantified by the following multiple regression model:

$$P(kg/mh) = -9.26 + 0.0594AVA + 11.79CBDia + 0.000953TQ - 0.484PSNP \quad ...7.20$$

B. Micro-Level Observation

The major buildability factors hypothesised to influence the reinforcing steel fixing labour productivity of slab panels at this level of observation are the characteristic bar diameter, quantity of reinforcement fixed, layer location of reinforcement and panel geometry. As with base and suspended flat slabs, different impacts of reinforcing steel quantity on labour productivity for the two monitored categories of slab geometry, i.e. rectangular versus non-rectangular, was hypothesised and incorporated into the regression model as an interaction term as shown in equation 7.21 below.

Two investigations were conducted at this level of observation. On the one hand, the total quantity of reinforcement fixed in both layers in the monitored slab panel was lumped and its associated labour input was applied to quantity the labour productivity of the activity. On the other, the quantity of reinforcement fixed in each observed layer, i.e. bottom and top, and its associated labour input was used to quantify the labour productivity of the relevant layer. The objectives of this approach were to quantify the overall impact of the panel geometry as well as the layer location on reinforcing steel fixing labour productivity.

1. Regression Model for the Total Quantity of Reinforcement Fixed in Both Layers of Slab Panels

The relationship between reinforcing steel labour productivity of slab panels and buildability factors at the micro-level is quantified by the following multiple interaction-regression model:

$$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,TQ + b_3\,GOP + b_4\,(GOP * TQ) \qquad ...7.21$$

Where CBDia and TQ, as previously defined, are the characteristic bar diameter and total quantity of reinforcement fixed in the observed slab panels respectively. GOP is a dummy variable which indicates the geometry of the observed slab and quantifies the average difference in fixing labour productivity between non-rectangular and rectangular slabs. It assumes the value of 0 if the slab is rectangular, and 1 if non-rectangular.

The overall regression model and coefficients statistics are shown in tables 7.26 and 7.27 respectively.

Table 7.26 Overall Regression Model Statistics for Micro-Level Reinforcing Steel Labour Productivity of Slab Panels for the Total Quantity of Reinforcement Fixed

Correlation Coefficient (R)	*85.74%*
Coefficient of Determination (R^2)	*73.51%*
Standard Error	*34.26*
$F(4,858)$	*595.24*
p-value	*0.000*
No. of Observations	*863*

Table 7.27 Regression Coefficients Statistics for Micro-Level Reinforcing Steel Labour Productivity of Slab Panels for the Total Quantity of Reinforcement Fixed

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
CBDia (mm)	*15.97*	*0.864*	*0.000*	*1.58*	*0.408*	*1*	*1.00*
TQ (kg)	*0.0864*	*0.0526*	*0.000*	*1.97*	*0.405*	*2*	*0.99*
GOP	*-44.66*	*2.96*	*0.000*	*1.53*	*N/A*	*N/A*	*N/A*
(GOP Q)*	*0.0523*	*0.0107*	*0.000*	*1.57*	*N/A*	*N/A*	*N/A*

The relationship between reinforcing steel fixing labour productivity and the relevant buildability factors is quantified by the following multiple regression model:

$$P(kg/mh) = -34.54 + 15.97\,CBDia + 0.0864\,TQ - 44.66\,GOP + 0.0523\,(GOP * TQ) \qquad \text{...7.22}$$

As shown in table 7.27, the characteristic bar diameter and the total quantity of reinforcement fixed have almost the same positive effect on labour productivity. The dummy variable GOP, which represents the average difference in labour productivity between fixing reinforcement in non-rectangular and rectangular slabs quantifies an overall average loss in labour productivity of 44.66 kg/mh associated with fixing reinforcement in non-rectangular slabs. Moreover, the coefficient of the interaction term between the total quantity of reinforcement fixed and slab geometry, quantifies a significant increase in the slope of the relationship between the quantity of reinforcement and labour productivity for the two categories of slab panels geometry, holding the characteristic bar diameter in the model constant.

Table 7.28 Average Values of Buildability Factors Influencing Micro-Level Reinforcing Steel Labour Productivity of Slab Panels for the Total Quantity of Reinforcement Fixed

Slab Panel Geometry	*Average Characteristic Bar Diameter (mm)*	*Average Total Quantity of Reinforcement Fixed (kg)*
Rectangular	*10.42*	*286.25*
Non-rectangular	*9.93*	*125.87*
Total	*10.23*	*224.18*

To quantify the average difference in labour productivity between fixing reinforcing steel bars in non-rectangular and rectangular slab panels, the average values of the corresponding buildability factors shown in table 7.28 are substituted into equation 7.22 for the relevant category of slab geometry as follows:

a) Non-rectangular Slab Panels, GOP = 1:

The average labour productivity of reinforcing steel fixing in non-rectangular slab panels, i.e. GOP = 1, is quantified as shown below:

$$\begin{aligned} P(kg/mh) = & -34.54 + 15.97(9.93) + 0.0864(125.87) \\ & -44.66(1) + 0.0523(1 * 125.87) = 96.84 \end{aligned}$$

b) Rectangular Slab Panels, GOP = 0:

The average labour productivity of reinforcing steel fixing in rectangular slab panels, i.e. GOP = 0, is quantified as shown below:

$$\begin{aligned} P(kg/mh) = & -34.54 + 15.97(10.42) + 0.0864(286.25) \\ & -44.66(0) + 0.0523(0 * 286.25) = 156.60 \end{aligned}$$

Therefore, the average percentage difference in labour productivity between non-rectangular and rectangular slab panel is determined as shown below:

$$\left[\frac{(156.60-96.84)}{156.60}\right]*100=38.16\% \qquad ...7.23$$

Thus, an average loss in labour productivity of about 38%, compared with rectangular slab panels, is estimated for fixing reinforcement in non-rectangular panels.

In comparison with the quantified average difference in reinforcing steel labour productivity of base and suspended flat slabs, the average difference in productivity between the two categories of slab panels geometry is approximately more than double, i.e. 15% versus 38% for base and suspended flat slabs, and slab panels respectively. This result is expected since the variability of reinforcing bar lengths in small compared to large panels is higher. Consequently, an additional labour input is required to locate the "right" bar lengths prior to the fixing process.

2. Regression Model for the Quantity of Reinforcement Fixed in each Monitored Layer of Slab Panels

The effect of layer location on reinforcing steel fixing labour productivity was determined by partitioning the labour inputs pertaining to each reinforcement layer, i.e. bottom and top, separately as was previously explained in chapter three. The relationship between labour productivity of slab panels and the relevant buildability factors at the micro-level is quantified by the following multiple regression model:

$$P(kg/mh)=b_0+b_1\,CBDia+b_2\,Q+b_3\,GOP+b_4\,(GOP*Q)+b_5\,LLoc \qquad ...7.24$$

The influence of layer location on labour productivity is quantified by introducing the dummy variable LLoc as shown in equation 7.24 above. LLoc indicates the monitored layer location and quantifies the average difference in labour productivity between fixing reinforcement in top and bottom layers; it assumes the value of 0 if the monitored layer is at the bottom level of the slab, and 1 if at the top.

The overall regression model and coefficients statistics are shown in tables 7.29 and 7.30 respectively.

Table 7.29 Overall Regression Model Statistics for Micro-Level Reinforcing Steel Labour Productivity of Slab Panels for the Monitored Layer Location

Correlation Coefficient (R)	*89.82%*
Coefficient of Determination (R^2)	*80.68%*
Standard Error	*32.69*
F(5,1010)	*843.53*
p-value	*0.000*
No. of Observations	*1016*

Table 7.30 Regression Coefficients Statistics for Micro-Level Reinforcing Steel Labour Productivity of Slab Panels for the Monitored Layer Location

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
CBDia (mm)	*20.67*	*0.670*	*0.000*	*1.57*	*0.535*	*1*	*1.00*
Q (kg)	*0.151*	*0.00682*	*0.000*	*1.78*	*0.409*	*2*	*0.76*
GOP	*-52.06*	*2.95*	*0.000*	*1.85*	*N/A*	*N/A*	*N/A*
(GOP * *Q)*	*0.0737*	*0.0134*	*0.000*	*1.86*	*N/A*	*N/A*	*N/A*
LLoc	*-32.69*	*3.23*	*0.000*	*1.27*	*N/A*	*N/A*	*N/A*

The relationship between reinforcing steel labour productivity and the relevant buildability factors is quantified by the following multiple regression model:

$$\boldsymbol{P(kg/mh) = -81.36 + 20.67\,CBDia + 0.151\,Q - 52.06\,GOP + 0.0737\,(GOP * Q) - 32.69\,LLoc} \quad \text{...7.25}$$

The dummy variable which represents the average difference in labour productivity between fixing reinforcement in non-rectangular and rectangular slabs quantifies an overall loss in labour productivity of 52.06 kg/mh associated with fixing reinforcement in non-rectangular slabs. The coefficient of the interaction term between the quantity of reinforcement fixed in the relevant monitored layer and slab geometry, quantifies a significant increase in the slope of the relationship between the quantity of reinforcement fixed and labour productivity between non-rectangular and rectangular slabs, holding the characteristic bar diameter and layer location constant.

Relative to the bottom layer, the regression coefficient of layer location dummy variable quantifies an overall, i.e. both categories of slab geometry, average loss of 32.69 kg/mh in labour productivity associated with fixing top layer reinforcing bars, holding all other variables in the model constant.

Table 7.31-a Average Values of Buildability Factors Influencing Micro-Level Reinforcing Steel Labour Productivity of Rectangular Slab Panels for the Monitored Layer Location

Layer Location	***Average Characteristic Bar Diameter (mm)***	***Average Total Quantity of Reinforcement Fixed (kg)***
Bottom	*10.41*	*196.34*
Top	*12.61*	*330.29*
Total	*10.88*	*225.00*

Table 7.31-b Average Values of Buildability Factors Influencing Micro-Level Reinforcing Steel Labour Productivity of Non-Rectangular Slab Panels for the Monitored Layer Location

Layer Location	***Average Characteristic Bar Diameter (mm)***	***Average Total Quantity of Reinforcement Fixed (kg)***
Bottom	*9.93*	*114.40*
Top	*11.11*	*425.67*
Total	*9.97*	*122.56*

To quantify the average percentage difference in labour productivity between fixing reinforcing steel bars in top and bottom layers of slab panels, the average values of the corresponding buildability factors shown in tables 7.31-a & b are substituted into equation 7.25 for the relevant category of slab geometry as follows:

a) Quantifying Average Percentage Difference in Labour Productivity between Top and Bottom Reinforcement layers in Rectangular Slabs

The average percentage difference in labour productivities between top and bottom layers fixed in rectangular slabs, i.e. GOP = 0, is quantified as follows:

- **Top Layer, LLoc = 1:**

$$P(kg/mh) = -81.36 + 20.67(12.61) + 0.151(330.29) - 52.06(0) + 0.0737(0*330.29) - 32.69(1) = 196.47$$

- **Bottom Layer, LLoc = 0:**

$$P(kg/mh) = -81.36 + 20.67(10.41) + 0.151(196.34) - 52.06(0) + 0.0737(0*196.34) - 32.69(0) = 163.46$$

Therefore, the average percentage difference in labour productivity between top and bottom reinforcement layers in rectangular slabs is determined as shown below:

$$\left[\frac{(196.47 - 163.46)}{163.46}\right]*100 = 20.19\% \qquad \text{...7.26}$$

Hence, an average gain in labour productivity of about 20%, in comparison with bottom layer, is estimated for fixing top layer reinforcing steel bars.

b) Quantifying Average Percentage Difference in Labour Productivity between Top and Bottom Reinforcement layers in Non-rectangular Slabs

The average percentage difference in labour productivities between top and bottom layers fixed in non-rectangular slabs, i.e. GOP = 1, is quantified as follows:

- **Top Layer, LLoc = 1:**

$$P(kg/mh) = -81.36 + 20.67(11.11) + 0.151(425.67) - 52.06(1) + 0.0737(1*425.67) - 32.69(1) = 159.18$$

- **Bottom Layer, LLoc = 0:**

$$P(kg/mh) = -81.36 + 20.67(9.93) + 0.151(114.40) - 52.06(1) + 0.0737(1*114.40) - 32.69(0) = 97.54$$

Thus, the average percentage difference in labour productivity between top and bottom reinforcement layers in non-rectangular slabs is quantified as follows:

$$\left[\frac{(159.18-97.54)}{97.54}\right]*100=63.19\% \qquad \ldots 7.27$$

Hence, an average gain in labour productivity of approximately 63%, in comparison with bottom layer, is estimated for fixing top layer reinforcing steel bars in non-rectangular slab panels.

The quantified results of this activity contradict the hypothesised influence of layer location on labour productivity and disagree with the finding obtained from the investigation conducted on base and suspended flat slabs activities.

However, a careful inspection of the average values of the characteristic bar diameter as well as the quantity of reinforcement fixed in the relevant layer for the two categories of the shape geometry shown in tables 7.10 and 7.31, shows that the difference in the average values of bar diameter and quantity of reinforcement fixed in slab panels top layers, compared with base and suspended flat slabs, are substantially larger than those fixed in bottom layers. Therefore, we may conclude that the impacts of reinforcing steel bar diameter and quantity of reinforcement on labour productivity are stronger than the impact of the layer location and overshadow its effect. Furthermore, the depth of the observed slab panels, compared with base and suspended flat slabs, is on average smaller, which might further facilitate lifting and fixing the top reinforcement layer.

7.5 Summary

The effects and relative influence of buildability factors on reinforcing steel fixing labour productivity of the various observed activities at both levels, macro and micro, were quantified using the ordinary least squares method. Regression and coefficients statistics at 0.050 significance level for the developed models were presented in table format. The unique and interaction effects of the relevant factors on labour productivity were quantified and the relative influence of variables was determined using standardised regression coefficients. The major findings of this investigation are summarised as follows:

1. A significant positive relationship between the characteristic bar diameter as well as quantity of reinforcement and labour productivity existed in all observed reinforcing steel activities.

2. Whilst the influence of the variability of element sizes on reinforcing steel labour productivity was insignificant in isolated foundations activity, a significant negative impact of this variable was exhibited in observed columns and beams activities.

3. The effect of geometry on reinforcing steel fixing labour productivity was investigated in bases, suspended flat slabs and slab panels, and consistent patterns were obtained. Since the procedure of fixing reinforcement in base slabs, i.e. rafts and ground slabs, and suspended flat slabs is identical, along with the hypothesised buildability factors influencing steel fixing labour productivity, the data points collected for these elements were lumped in a single data file and analysed collectively. In comparison with rectangular shapes, on average, a quantified loss of 15% in labour productivity was associated with fixing reinforcement in non-rectangular bases and suspended flat slabs. On the other hand, slab panels were analysed separately where an average loss of 38% in labour productivity was associated with fixing reinforcement in non-rectangular compared to rectangular panels.

4. Fixing reinforcement in top layers of base and suspended flat slabs, compared with bottom layers, was associated with a significant loss in labour productivity. The average quantified productivity loss in rectangular and non-rectangular slabs were 15% and 13% respectively, indicating almost a consistent loss in labour productivity between the two categories of slab geometry. In contrast to the results obtained from analysing the data collected in observed base and suspended flat slabs activities, higher labour productivity was quantified in top layers of monitored slab panels. However, upon inspection of the average values of the characteristic bar diameter and quantity of reinforcement fixed in slab panels top reinforcement layers, it was found that the difference in the average values of these factors, compared with base and suspended flat

slabs, was substantially larger than those fixed in bottom layers. As a result, the quantified results indicate that the effects of reinforcing steel diameter and quantity of reinforcement on labour productivity are more influential than the impact of layer location and overshadow its effect.

5. The presence of circular columns had a significant negative influence on macro-level labour productivity. The influence was determined by the relationship between labour productivity and the percentage of reinforcement fixed in circular columns within the total monitored columns of the activity. On average, an overall loss in micro-level labour productivity of 38%, compared with rectangular columns, was associated with fixing reinforcement in circular columns.

6. A significant positive relationship between wall thickness and reinforcing steel fixing labour productivity was determined.

7. Compared with fixing 8 mm in diameter stirrups in beams, a significant average loss of 10% in macro-level labour productivity was associated with fixing 10 mm stirrup. Moreover, the quantified effects of width and depth of observed beams revealed significant impacts on labour productivity. A significant decrease in labour productivity was associated with the increase of width and depth of beams at both levels of observation, macro and micro.

8. The ratio of the quantity of reinforcement fixed in curved beams to the total reinforcement quantity fixed in all beams, expressed as a percentage, was used to quantify the negative impact of the presence of curved beams on macro-level labour productivity. Moreover, the average difference in micro-level labour productivity between curved and linear beams was determined for both specified stirrup diameters, i.e. 8 mm and 10 mm, and the quantified results were consistent. On average, compared with linear beams, a loss of 38% in reinforcing steel labour productivity was associated with fixing reinforcement in curved beams.

Chapter Eight

Analysis of Concreting and Trowelling Productivities

8.1 Introduction

Buildability factors hypothesised to impact concreting and floor trowelling labour productivities were introduced and discussed in chapter three. In this chapter, the effects and relative influence of these factors are presented and discussed. The observed concreting trade comprised two distinct placement methods; pumped and skipped. As we have previously explained in chapter three, skipped concrete is the preferred placement method in vertical members, i.e. columns and walls, due to the susceptibility of such members to lateral pressure especially when the traditional formwork is the used material. Since the two placement methods were conducted in two different populations, i.e. horizontal versus vertical elements, in order to validate the findings of this investigation, separate analysis was conducted for each element category.

When the specified surface finish of the concreted floor was of the power-trowelled type, the trowelling activity was monitored separately, and the labour productivity was quantified based on the finished area and productive labour inputs used to complete the activity.

8.2 Data Distribution

A total of 420 and 400 productivity data points were collected for pumped and skipped concrete respectively. According to the specified slump, concrete workability was classified as high, medium or low. As we have previously explained in chapter three, a consistent approach for concrete workability classification was used in all observed concreting activities. The workability classification scheme used throughout this study was previously presented in chapter three (table 3.16).

A. Pumped Concrete

A total of 420 productivity data points of pumped concrete were collected. According to the adopted concrete workability classification, the total data points were further distributed as follows:

1. High workability mix, 110 data points
2. Medium workability mix, 199 data points
3. Low workability mix, 111 data points

B. Skipped Concrete

A total of 400 productivity data points of skipped concrete were collected. As was previously indicated, the skipped concrete productivity data were observed in only vertical members, i.e. columns and walls. Collected skipped concrete productivity data were distributed according to the observed concrete workability as follows:

1. High workability mix, 106 data points
2. Medium workability mix, 200 data points
3. Low workability mix, 94 data points

C. Trowelling

A total of 104 productivity data points of power-trowelled surface finish were collected. A maximum of four trowelling machines used simultaneously were observed in any single floor.

8.3 Concreting Labour Productivity

Volume of concrete, height above ground level, steel congestion ratio and concrete workability were the major buildability factors hypothesised to influence pumped and skipped concrete labour productivity. As was previously explained in chapter three, concrete workability was classified as high, medium or low based upon the specified slump. The effect of workability on concreting labour productivity was quantified by introducing a three-category dummy variable into the multiple regression model. Medium workability was chosen to be the base or reference category and therefore was omitted from the regression model. The quantified regression coefficients of the remaining two categories in the model, i.e. high and low workability, would then quantify the average difference in concreting labour productivity between the reference category and the corresponding present categories of concrete workability.

Regression coefficients previously presented in chapter five were quantified and the relative influence of such factors was determined using the standardisation technique. Regression coefficients represent the unique effects of the relevant buildability factors on concreting labour productivity. The impacts of all hypothesised buildability factors on labour productivity are statistically significant at 0.050 significance level. Furthermore, the Variance Inflation Factors (VIF) amongst the variables are below the cut-off value of 10, indicating reasonable correlations and therefore reliable estimates of all quantified regression coefficients.

With the exception of the effect of the number of trowelling machines used to conduct the activity, the influence of all buildability factors on labour productivity are in accordance with the hypothesised effects previously discussed in chapter three. Results of regression analyses of the various monitored activities are presented.

8.3.1 Pumped Concrete

The relationship between buildability factors and pumped concrete labour productivity is determined by the following multiple regression model:

$$P(m^3 / mh) = b_0 + b_1 V + b_2 H + b_3 \, SCR + b_4 \, HWRK + b_5 \, LWRK$$

Where V = volume of poured concrete; H = height above ground level; SCR = steel congestion ratio; and HWRK as well as LWRK are dummy variables representing high and low concrete workability respectively. As was previously explained in chapter five, the value of one is substituted into the corresponding observed workability of placed concrete, whilst the value of zero is assumed for the other category of concrete workability in the regression model.

The overall regression model and coefficients statistics are presented in tables 8.1 and 8.2 respectively.

Table 8.1 Overall Regression Model Statistics for Pumped Concrete Labour Productivity

Correlation Coefficient (R)	*92.88%*
Coefficient of Determination (R^2)	*86.27%*
Standard Error	*0.286*
F(5,414)	*520.40*
p-value	*0.000*
No. of Observations	*420*

Table 8.2 Regression Coefficients Statistics for Pumped Concrete Labour Productivity

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
V (m^3)	*0.00322*	*0.000*	*0.000*	*1.04*	*0.535*	*1*	*1.00*
H (m)	*-0.0238*	*0.00246*	*0.000*	*1.11*	*-0.186*	*2*	*0.35*
SCR (kg/m^3)	*-0.00181*	*0.000*	*0.000*	*1.10*	*-0.0965*	*3*	*0.18*
HWRK	*0.768*	*0.0343*	*0.000*	*1.17*	*N/A[1]*	*N/A*	*N/A*
LWRK	*-1.03*	*0.0345*	*0.000*	*1.19*	*N/A[1]*	*N/A*	*N/A*

[1]Dummy variables are used to quantify differences in levels between or amongst categories, therefore, the normal interpretation for standardised coefficients does not apply.

The relationship between pumped concrete labour productivity and the relevant buildability factors is therefore determined by the following multiple regression model:

$$\begin{aligned} P(m^3/mh) = {} & 2.31 + 0.00322V - 0.0238H - 0.00181SCR \\ & + 0.768HWRK - 1.03LWRK \end{aligned} \qquad \ldots 8.1$$

The regression coefficients of dummy variables quantify an average gain of 0.768 m^3/mh in labour productivity consorted with high concrete workability, and an average loss of 1.03 m^3/mh associated with low concrete workability relative to the medium concrete workability.

In order to quantify the average percentage gain and loss in labour productivity relative to the reference category, the average values of the buildability factors shown in table 8.3 are substituted into equation 8.1 for the corresponding category of concrete workability as follows:

Table 8.3 Average Values of Buildability Factors Influencing Pumped Concrete Labour Productivity

Design Variable	*High Workability*	*Medium Workability*	*Low Workability*	*Total*
V (m^3)	*61.31*	*87.36*	*120.91*	*89.40*
H (m)	*4.32*	*3.82*	*1.62*	*3.37*
SCR (kg/m^3)	*103.18*	*115.11*	*104.48*	*109.18*

A. Quantifying Average Percentage Difference in Pumped Concrete Labour Productivity between Medium and High Workability Mix Design

The average percentage difference in labour productivity between medium and high concrete workability is quantified as follows:

- **Medium Workability Concrete**

$$P(m^3 / mh) = 2.31 + 0.00322(87.36) - 0.0238(3.82) - 0.00181(115.11) + 0.768(0) - 1.03(0) = 2.29$$

- **High Workability Concrete**

$$P(m^3 / mh) = 2.31 + 0.00322(61.31) - 0.0238(4.32) - 0.00181(103.18) + 0.768(1) - 1.03(0) = 2.99$$

Therefore, the average percentage difference in labour productivity between medium and high workability concrete mix is determined as follows:

$$\left[\frac{(2.99 - 2.29)}{2.99}\right] * 100 = 23.41\% \qquad \text{...8.2}$$

Hence, an average approximate loss in labour productivity of 23%, compared with high workability, is associated with specifying medium concrete workability.

B. Quantifying Average Percentage Difference in Pumped Concrete Labour Productivity between Medium and Low Workability Mix Design

The average percentage difference in labour productivity between medium and low concrete workability is quantified as follows:

- **Medium Workability Concrete**

$$P(m^3/mh) = 2.31 + 0.00322(87.36) - 0.0238(3.82) - 0.00181(115.11) + 0.768(0) - 1.03(0) = 2.29$$

- **Low Workability Concrete**

$$P(m^3/mh) = 2.31 + 0.00322(120.91) - 0.0238(1.62) - 0.00181(104.48) + 0.768(0) - 1.03(1) = 1.44$$

Thus, the average percentage difference in labour productivity between medium and low workability concrete mix is quantified as shown below:

$$\left[\frac{(2.29 - 1.44)}{1.44}\right] * 100 = 59.03\% \qquad \ldots 8.3$$

Hence, an average gain in labour productivity of 59%, in comparison with low workability, is consorted with specifying medium concrete workability.

Similarly, the average percentage difference in labour productivity between low and high concrete workability is quantified as follows:

$$\left[\frac{(2.99 - 1.44)}{1.44}\right] * 100 = 107.64\% \qquad \ldots 8.4$$

Therefore, an average gain of approximately 108% in labour productivity, compared with low concrete workability, is associated with specifying high workability mix.

8.3.2 Skipped Concrete

The relationship between the buildability factors and skipped concrete labour productivity is quantified by the following multiple regression model:

$$P(m^3/mh) = b_0 + b_1 V + b_2 H + b_3\ SCR + b_4\ HWRK + b_5\ LWRK$$

Where, as previously defined, V, H, SCR, HWRK and LWRK are volume of poured concrete, height above ground level, steel congestion ratio and dummy variables representing high and low concrete workability respectively.

The overall regression model and coefficients statistics are presented in tables 8.4 and 8.5 respectively.

Table 8.4 Overall Regression Model Statistics for Skipped Concrete Labour Productivity

Correlation Coefficient (R)	88.49%
Coefficient of Determination (R^2)	78.30%
Standard Error	0.174
F(5,394)	284.36
p-value	0.000
No. of Observations	400

Table 8.5 Regression Coefficients Statistics for Skipped Concrete Labour Productivity

Coefficient	Value	Standard Error	p-value	VIF	Standardised Coefficient Value	Influence Rank	Relative Influence
V (m^3)	0.00618	0.000	0.000	1.11	0.474	1	1.00
H (m)	-0.00834	0.000	0.000	1.11	-0.215	3	0.45
SCR (kg/m^3)	-0.000956	0.000	0.000	1.01	-0.216	2	0.46
HWRK	0.359	0.0213	0.000	1.17	N/A	N/A	N/A
LWRK	-0.326	0.0218	0.000	1.13	N/A	N/A	N/A

The relationship between skipped concrete labour productivity and the relevant factors is quantified by the following multiple regression model:

$$\begin{aligned} P(m^3/mh) = {} & 1.04 + 0.00618V - 0.00834H - 0.000956SCR \\ & + 0.359HWRK - 0.326LWRK \end{aligned} \qquad \ldots 8.5$$

The regression coefficients of the dummy variables quantify an average gain of 0.359 m^3/mh in labour productivity associated with high concrete workability, and an average loss of 0.326 m^3/mh consorted with low concrete workability relative to the reference category, i.e. medium concrete workability.

Similar to the approach used in pumped concrete productivity, in order to quantify the average percentage gain and loss in labour productivity relative to the reference category, the average values of the buildability factors shown in table 8.6 are substituted into equation 8.5 for the corresponding category of concrete workability as follows:

Table 8.6 Average Values of Buildability Factors Influencing Skipped Concrete Labour Productivity

Design Variable	*High Workability*	*Medium Workability*	*Low Workability*	*Total*
V (m^3)	*11.29*	*17.77*	*18.35*	*16.19*
H (m)	*7.61*	*10.00*	*10.02*	*9.37*
SCR (kg/m^3)	*213.30*	*233.22*	*220.34*	*224.92*

A. Quantifying Average Percentage Difference in Skipped Concrete Labour Productivity between Medium and High Workability Mix Design

The average percentage difference in labour productivity between medium and high concrete workability is quantified as follows:

- **Medium Workability Concrete**

$$\begin{aligned} P(m^3/mh) = {} & 1.04 + 0.00618(17.77) - 0.00834(10.00) - 0.000956(233.22) \\ & + 0.359(0) - 0.326(0) = 0.843 \end{aligned}$$

- **High Workability Concrete**

$$P(m^3/mh) = 1.04 + 0.00618(11.29) - 0.00834(7.61) - 0.000956(213.30) \\ + 0.359(1) - 0.326(0) = 1.20$$

Hence, the average percentage difference in skipped labour productivity between medium and high workability concrete mix is quantified as shown below:

$$\left[\frac{(1.20 - 0.843)}{1.20}\right] * 100 = 29.75\% \qquad \ldots 8.6$$

Thus, an average loss in labour productivity of approximately 30%, compared with high workability, is consorted with specifying medium concrete workability.

B. Quantifying Average Percentage Difference in Skipped Concrete Labour Productivity between Medium and Low Workability Mix Design

The average percentage difference in labour productivity between medium and low concrete workability is quantified as follows:

- **Medium Workability Concrete**

$$P(m^3/mh) = 1.04 + 0.00618(17.77) - 0.00834(10.00) - 0.000956(233.22) \\ + 0.359(0) - 0.326(0) = 0.843$$

- **Low Workability Concrete**

$$P(m^3/mh) = 1.04 + 0.00618(18.35) - 0.00834(10.02) - 0.000956(220.34) \\ + 0.359(0) - 0.326(1) = 0.533$$

Hence, the average percentage difference in labour productivity between medium and low workability concrete mix is quantified as follows:

$$\left[\frac{(0.843-0.533)}{0.533}\right]*100=58.16\% \qquad ...8.7$$

Therefore, an average gain in labour productivity of approximately 58%, compared with low workability, is associated with specifying medium concrete workability.

Following the same approach, the average percentage difference in skipped concrete labour productivity between low and high concrete workability is quantified as follows:

$$\left[\frac{(1.20-0.533)}{0.533}\right]*100=125.14\% \qquad ...8.8$$

Thus, an average gain of approximately 125% in labour productivity, compared with low concrete workability, is consorted with specifying high workability mix.

The quantified average differences in labour productivity amongst the specified workability of concrete show a consistent pattern between the two placement methods. Whilst an average loss in pumped concrete labour productivity of 23% is quantified as a result of specifying medium concrete workability relative to the high category, an average loss in skipped concrete labour productivity of 30% is determined. Moreover, the average percentage gain in labour productivity due to pouring medium workability concrete, compared with low workability mix, is 59% for pumped as opposed to 58% for skipped concrete. Finally, an average gain of 108% in concrete labour productivity is associated with pumping high relative to low workability mix, whilst the difference between the two categories is 125% for skipped concrete.

However, upon inspecting the quantified average differences in labour productivity amongst the three categories of both placement methods, especially between high and low workability categories, we realise a stronger impact of concrete workability on labour productivity associated with skipped concrete. One reason for this effect might be attributed to the mechanism of the two investigated placing methods. Whilst the pump pressure can be increased to minimise the difficulty encountered in discharging medium to low slump concrete, skipped concrete lakes such an advantage. Discharging skipped concrete relies on gravity when the skip operator manually opens the shoot for the concrete to flow under its own weight. Consequently, when low slump concrete is skipped, the discharging process becomes difficult and slow. It is worth noting that the researcher witnessed, on several observed sites, where the specified workability was of the low category, the concrete being vibrated inside the skip to facilitate the discharging process.

Another reason may be due to the difficulty of vibrating the concrete in vertical as opposed to horizontal members. Vibrating the concrete in vertical members is performed whilst labours are either standing on ladders or scaffoldors as the case with columns and walls respectively. On the one hand, the manoeuvring process of labours at this position is hindered, and on the other, reaching the bottom part of vertical members with poker vibrators is difficult compared with horizontal shallow members. In view of this, specifying medium or low slump concrete would further exacerbate skipped concrete labour productivity.

Furthermore, and although the volume of placed concrete remains the most influential variable on concreting labour productivity of the two observed casting methods, we realise a shift in the relative importance of height and steel congestion ratio between pumped and skipped concrete as shown in tables 8.2 and 8.5. Whilst the height above ground level has a stronger impact on pumped labour productivity than the steel congestion ratio, the opposite is true in skipped concrete. Again, this shift in the relative influence between the two variables on labour productivity is most likely attributed to the previously explained difficulty encountered in the vibration process of concreting vertical members, let alone the negative effect of steel congestion on the activity.

8.4 Trowelling Productivity

Variables hypothesised to influence the productivity of power trowelled concrete floors were investigated. Major investigated variables included the floor area as well as the number of trowelling machines used.

For the reasons previously illustrated in chapter three, we hypothesise that a positive relationship between floor area and trowelling productivity exists. Moreover, as the trowelled floor area increases, multiple machines would be used to conduct the activity efficiently and within reasonable timeframe.

The labour productivity of the monitored trowelling activity is quantified based on the surface area finished and its associated labour input. The relationship between the previously stated variables and the trowelling productivity is quantified by the following multiple regression model:

$$P(m^2 / mh) = b_0 + b_1 A + b_2 NOM$$

Where A = trowelled floor area, and NOM = number of trowelling machines used in the activity.

The overall regression model and coefficients statistics are presented in tables 8.7 and 8.8 respectively.

Table 8.7 Overall Regression Model Statistics for Trowelled Concrete Productivity

Correlation Coefficient (R)	*89.06%*
Coefficient of Determination (R^2)	*79.31%*
Standard Error	*3.07*
F(2,101)	*193.57*
p-value	*0.000*
No. of Observations	*104*

Table 8.8 Regression Coefficients Statistics for Trowelled Concrete Productivity

Coefficient	***Value***	***Standard Error***	***p-value***	***VIF***	***Standardised Coefficient Value***	***Influence Rank***	***Relative Influence***
A (m^2)	*0.0469*	*0.00239*	*0.000*	*2.20*[1]	*1.32*	*1*	*1.00*
NOM	*-9.13*	*0.674*	*0.000*		*-0.910*	*2*	*0.69*

[1]Variance inflation factor indicating the correlation between the trowelled area and number of trowelling machines in the model.

The relationship between trowelled productivity and the relevant variables is quantified by the following multiple regression model:

$$P(m^2/mh) = 34.73 + 0.0469\,A - 9.13\,NOM \qquad \ldots 8.9$$

The impact of the number of machines used in the trowelling activity contradicts our hypothesis. Whilst we have hypothesised a positive relationship between productivity and the number of machines, the quantified influence, as shown in table 8.8, indicates otherwise. On average, trowelling productivity decreases by 9.13 m^2/mh as the number of machines increases by one, holding the trowelled floor area constant.

The reason for this finding might be due to overcrowding. There is evidence to suggest that a labour density greater than one man per 30 m^2 would lead to decrease in productivity [60], and the trowelling activity is no exception. However, within the activity, it is necessary to differentiate between using multiple trowelling machines because of the large floor area requirements, and those which employ multiple machines simply to accelerate the activity. In the later case, it is likely that over manning leads to overcrowding and therefore sub-optimal labour density.

In view of the previous discussion, the finding also indicates that for a given floor area, there is an optimum number of trowelling machines which would lead to optimum trowelling productivity. The question of the optimum number of trowelling machines associated with floor areas however is beyond the scope of this research, and would be recommended that this subject be further explored.

8.5 Summary

Factors influencing concreting and trowelling labour productivity were quantified using the ordinary least squares method. Regression and coefficients statistics at 0.050 significance level for the developed regression models were presented in table format. Pumped concrete was observed in horizontal members whereas skipped concrete was limited to vertical columns and walls. When the specified surface finish of concrete floors was of the power-trowelled type, the labour input of the trowelling activity was monitored separately.

The unique effects of the relevant variables on pumped, skipped and trowelling labour productivity were quantified and the relative influence of these variables was determined using standardised regression coefficients. The major findings of this investigation are summarised as follows:

1. Volume of placed concrete, height above ground level, steel congestion ratio and concrete workability were amongst the major factors hypothesised to influence pumped and skipped concrete labour productivity.

2. For pumped and skipped casting methods, volume of placed concrete was the most influential factor on concreting labour productivity. As the volume of concrete placed increases, so does the labour productivity.

3. For both placement methods, , i.e. pumped and skipped concrete, height above ground level and steel congestion ratio had significant negative impacts on labour productivity of the concreting activity.

4. Concrete workability, classified according to the slump values as high, medium and low, had a significant influence on labour productivity of pumped and skipped concrete. For both placing methods, as the concrete workability decreases, the labour productivity decreases too. Although a consistent pattern between the two placement methods, i.e. pumped and skipped concrete, was realised, the quantified average differences in labour productivity amongst the specified workability of concrete were different for the two placement methods. Whilst an average loss in pumped concrete labour productivity of 23% was determined as a result of placing medium concrete workability relative to the high category, an average of loss in skipped concrete labour productivity of 30% was quantified. In addition, the average percentage gain in labour productivity due to placing medium workability concrete, compared to low workability, was 59% for pumped versus 58% for skipped concrete. Furthermore, an average difference of 108% gain in labour productivity was associated with pumping high relative to low workability mix, whereas a difference of 125% between the two categories was determined for skipped concrete.

5. Although the volume of placed concrete had the strongest positive impact on concreting labour productivity of pumped and skipped concrete, a shift in the relative influence of height and steel congestion ratio between the two placement methods was determined. Whilst height above ground level had a stronger negative effect on pumped labour productivity than the steel congestion ratio, the opposite was true for skipped concrete. This shift in the relative influence between the two variables on labour productivity might be attributed to the difficulty encountered in the vibration process of concreting vertical members, especially as the steel congestion ratio in members increases.

6. The area of trowelled floors and the number of machines used in the process were the two major variables hypothesised to impact the productivity of the trowelling activity. Whilst a positive relationship was quantified between the floor area and the trowelling productivity, the number of machines used in the activity had a negative influence on the productivity. This finding could be attributed to overcrowding of trowelling machines within the floor area, and indicates that for a given floor area, there is an optimum number of machines which would lead to optimum trowelling productivity.

Chapter Nine

Analysis of the Applicability of Learning Curve Theory to *in situ* Reinforced Concrete Construction

9.1 Introduction

Due to its simplicity, the straight-line learning curve model is most commonly used for construction activities. An investigation into the applicability of learning curve theory using the unit straight-line model was conducted on formwork, reinforcing steel fixing and pumped concrete trades. Multi-storey buildings having identical recurring floors were selected for this study. The influence on labour productivity due to learning was quantified by investigating the change in labour inputs, i.e. man-hours, as the floor or cycle number increased.

The input for each cycle or floor and its associated cycle number within the monitored building, were first plotted against each other to visualise the relationship between man-hours and cycle numbers. The straight line curves were then obtained by transforming the unit data into natural logarithmic values. Finally, the method of least squares was used to fit the plotted data and test the significance of the slope of the relationship between man-hours and cycle number. According to learning curve theory, we would expect the slope of the fitted straight line to be significantly negative.

9.2 Data Analysis Concept

Multi-storey buildings having identical recurring formwork configurations, beams and slab panels as well as a constant volume of concrete pumped on each floor were selected for investigating the effect of learning phenomenon on formwork, reinforcing steel fixing and pumped concrete labour productivity. Although it would have been a useful cross-reference, craned or skipped concrete investigation was not possible and could not be conducted. Observed skipped concrete was limited to vertical elements, i.e. columns and walls, and the output of these elements within an observed building, i.e. cubic meters of concrete poured, was not constant throughout the building floors due to the reduction in the cross sections as the number of floor or cycle increases. Skipped concrete data which met the fundamental assumption of recurring outputs were of few cycles; hardly the basis for a meaningful and reliable investigation. On the other hand, pumped concrete volume of repeated identical building floors remained constant throughout the activity.

As was previously indicated in chapter three, in order to minimise the effect of material repetition and unravel the influence of learning on formwork labour productivity, the input of the first cycles, i.e. results from the first floor and any floor in which formwork material has been replaced, were discarded from the analysis. Moreover, to minimise the effect of delays on the learning curve pattern, only productive labour inputs were used throughout this investigation.

The unit straight-line learning curve for all trades observed was fitted using simple linear regression. The relationship between labour inputs and cycle numbers at 0.050 significance level was determined by the following power function model:

$$\textbf{Man} - \textbf{Hours} = T_1 * (\textbf{Cycle No.})^b \qquad \text{...9.1}$$

The model shown in equation 9.1 can be also expressed as straight-line unit model equation as we have previously illustrated in chapter five using equation 5.9. The learning rate (S), expressed as a percentage, is quantified using equation 5.8.

9.3 Analysis of the Effect of Learning on Formwork Productivity

Table 9.1 presents a sample of data used to plot the unit learning curve for one of the twenty-one different multi-storey buildings observed.

Table 9.1 Sample Data for Formwork Learning Curve Investigation of Recurring Floors

Project No. 0328-8			
Man-Hours ***(1)***	***Ln Man-Hours*** ***(2)***	***Cycle No.*** ***(3)***	***Ln Cycle No.*** ***(4)***
297.00	*5.69*	*1*	*0*
324.00	*5.78*	*2*	*0.693*
315.00	*5.75*	*3*	*1.10*
312.00	*5.74*	*4*	*1.39*
302.00	*5.71*	*5*	*1.61*
309.00	*5.73*	*6*	*1.79*
303.00	*5.71*	*7*	*1.95*
306.00	*5.72*	*8*	*2.08*
302.00	*5.71*	*9*	*2.20*

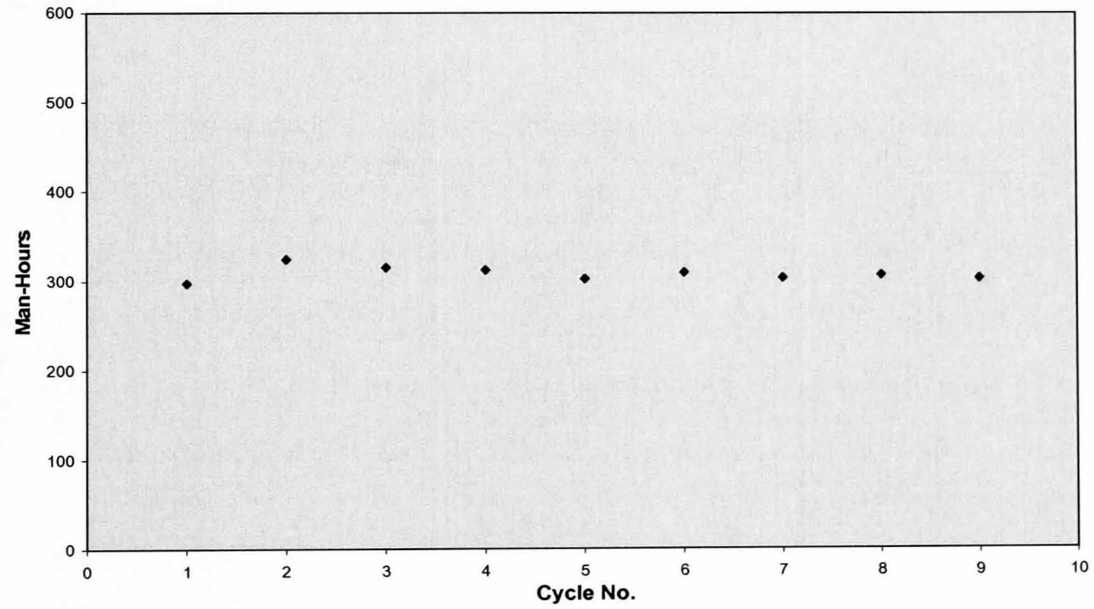


Figure 9.1 Relationship between Recurring Floors Formwork Inputs and Cycle Numbers in a Multi-storey Building

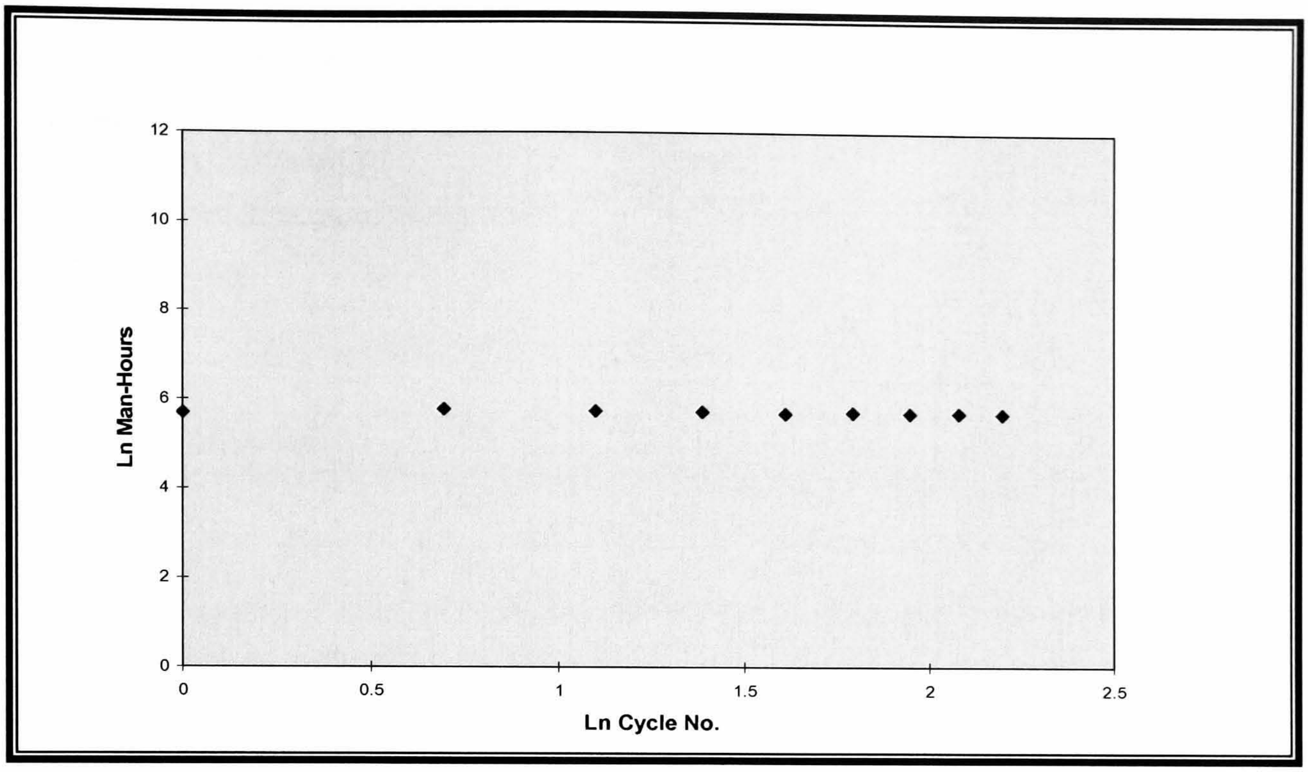


Figure 9.2 Relationship between Recurring Floors Formwork Natural Log Inputs and Cycle Numbers in a Multi-storey Building

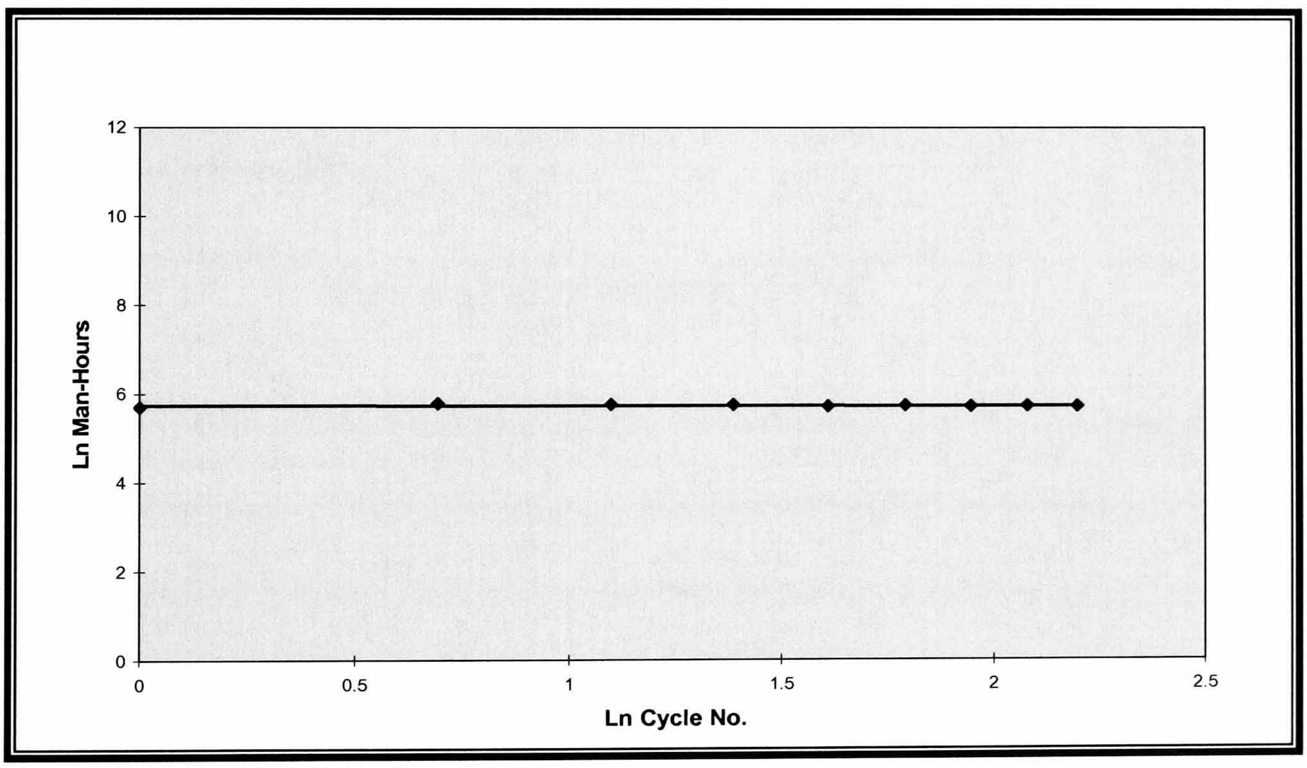


Figure 9.3 Formwork Learning Curve (Unit Natural Log – Recurring Floors)

The unit straight-line learning curve shown in figure 9.2 is fitted using simple linear regression. The overall regression model and coefficients statistics are presented in tables 9.2 and 9.3 respectively.

Table 9.2 Overall Regression Model Statistics for the Relationship between Formwork Labour Inputs and Cycle Numbers of Monitored Recurring Floors

Correlation Coefficient (R)	*15.39%*
Coefficient of Determination (R^2)	*2.37%*
Standard Error	*0.0281*
F(1,7)	*0.170*
p-value	*0.693*
No. of Observations	*9*

Table 9.3 Regression Coefficients Statistics for the Relationship between Formwork Labour Inputs and Cycle Numbers of Monitored Recurring Floors

Coefficient	***Value***	***Standard Error***
Intercept	*5.74*	*0.0217*
Cycle No.	*-0.00568*	*0.0138*

The relationship between the man-hours and cycle numbers is therefore presented by the following straight-line unit model equation:

$$\boldsymbol{Man-Hour = 5.74 - 0.00568\,Cycle\,No.} \qquad \ldots 9.2$$

Even though there is a negative relationship between the man-hours and cycle numbers as shown in equation 9.2, the influence of the cycle numbers on the observed inputs of repeated floor formwork is statistically insignificant (p-value > 0.050). The result indicates that the slope is insignificantly different from zero. The unit straight-line learning curve for the recurred observed floors pertaining to this sample data for one of the observed buildings is shown in figure 9.3.

To transform the straight-line model shown in equation 9.2 into a power function format, the labour input of the first cycle (T) is determined by substituting the intercept value shown in equation 9.2, i.e. 5.74, into equation 5.10 as follows:

$$\boldsymbol{T = e^{5.74} = 311.08}$$

The learning rate (S), expressed as a percentage, is quantified by substituting the slope (b) shown in equation 9.2, i.e. -0.00568, into equation 5.8 as follows:

$$S = (2^{-0.00568}) * 100 = 99.61\%$$

Therefore, the standard power function format of the learning curve of this sample project is quantified as shown below:

$$Man - Hours = 311.08 * Cycle\ No.^{-0.00568}$$

In view of the results presented for this sample project, it can be seen that despite the repetition of the observed floors, the formwork activity did not exhibit any significant productivity improvement as the cycle number of the monitored floors increased. According to the learning curve theory, the lower the learning rate, the higher the amount of productivity improvement. Consequently, the quantified learning rate of 99.61% indicates that basically no productivity improvement has taken place in the process of forming nine identical recurring floors.

Table 9.4 summarises the results of the learning curve investigation for formwork on all observed recurring floors. It can be seen from the table that none of the twenty-one monitored buildings exhibited any improvement in labour productivity due to repetition of floor formwork activities. In fact, fifteen buildings, or approximately 71% of the total monitored buildings, and in contrast to the expected reduction in labour input as the sequence number of recurring floor cycles increases, showed an increase rather than a decrease in labour inputs. In the few cases in which a decrease in the labour inputs was exhibited as the floor number increased, none was statistically significant in its influence on formwork labour productivity.

Table 9.4 Results Summary for the Investigation of the Applicability of Learning Curve Theory to Formwork Trade

Project No.	Total No. of Observed Cycles	Coefficient of Correlation (%R)	Coefficient of Determination (%R^2)	Learning Rate (S)[3] (%)	Influence of Learning on Formwork Productivity[4]
0201	4	57.93	33.55	102.00	N/A
0203	5	51.90	26.94	101.00	N/A
0204	5	61.12	37.36	102.00	N/A
0213-a[1]	8	9.78	0.96	100.00	N/A
0213-b[1]	8	13.15	1.73	100.00	N/A
0302-a[2]	4	36.81	13.55	100.00	N/A
0302-b[2]	5	96.88	93.86	103.00	N/A
0304	5	98.49	97.00	104.00	N/A
0305-a[2]	5	93.07	86.62	103.00	N/A
0305-b[2]	3	96.17	92.48	104.00	N/A
0324	6	61.51	37.83	103.00	N/A
0326-a[1]	5	24.08	5.80	99.22	Insignificant
0326-b[1]	5	45.47	20.67	101.00	N/A
0328-1	7	32.01	10.25	100.00	N/A
0328-2	6	31.09	9.66	100.00	N/A
0328-3	6	69.76	48.66	96.60	Insignificant
0328-4	6	43.55	18.96	99.62	Insignificant
0328-5	7	8.83	0.78	99.93	Insignificant
0328-6	6	76.05	57.83	97.82	Insignificant
0328-7	7	71.48	51.09	98.94	Insignificant
0328-8	9	15.39	2.37	99.61	Insignificant
0328-9	7	57.92	33.55	99.72	Insignificant
0328-10	6	16.31	2.66	100.00	N/A

[1]The monitored project comprised two identical buildings.

[2]Two analyses were conducted on the same monitored building due to forms replacement.

[3]A learning rate value of 100% indicates that no learning has taken plane. A value greater than 100% indicates that, in contrast to the learning curve theory principle, actually there is a positive relationship between man-hours and cycle numbers, i.e. man-hours increase as the cycle number increases. In both cases, the learning curve theory is inapplicable to the monitored floor formwork.

[4]An insignificant influence of learning on formwork labour inputs indicates that, although there is a negative relationship between cycle numbers and formwork labour inputs, i.e. inputs decrease as the cycle number increases, its impact has no statistical significance.

9.4 Analysis of the Effect of Learning on Reinforcing Steel Productivity

The investigation of the effect of learning on reinforcing steel fixing labour productivity involved fixing reinforcement in recurring beams and slab panels. The procedure used in formwork investigation was also employed in these activities. However, unlike the formwork investigation, the effect of material repetition has no influence on the learning process of this trade, and therefore all floors, i.e. cycles in the monitored buildings, were included in the analysis.

9.4.1 Analysis of the Effect of Learning on Reinforcing Steel Productivity of Beams

Table 9.5 summarises the results of the learning curve investigation for reinforcing steel fixing on all observed recurring beams. It can be noticed from the table that there is a sporadic pattern of the effect of learning on fixing beam reinforcement activity. Whilst the influence of learning phenomenon was exhibited in some monitored buildings, others, either showed an insignificant reduction in labour inputs as the cycle number increased, or to the contrary, an increase in labour inputs was associated with the increase of floor cycle numbers. Based on the developed learning curves of the nineteen monitored buildings, only 31% exhibited significant reduction in labour inputs as a result of repetition. Moreover, buildings in which a significant impact of learning on labour inputs was determined, none of the learning rates actually fell in the expected range of 70% to 90% as the case for most construction activities [83]. In fact, the quantified Learning rates shown in table 9.5 indicate that either no or little productivity improvement has taken place in the process of fixing reinforcing steel in identical recurring beams.

Table 9.5 Results Summary for the Investigation of the Applicability of Learning Curve Theory to Reinforcing Steel Trade – Recurring Beams

Project No.	***Total No. of Observed Cycles***	***Coefficient of Correlation (%R)***	***Coefficient of Determination (%R^2)***	***Learning Rate (S)[2] (%)***	***Influence of Learning on Reinforcing Steel Productivity[3]***
0201	*5*	*17.09*	*2.92*	*100.00*	*N/A*
0203	*6*	*44.00*	*19.37*	*98.55*	*Insignificant*
0204	*6*	*6.86*	*0.471*	*99.77*	*Insignificant*
302	*11*	*17.94*	*3.22*	*100.00*	*N/A*
304	*5*	*42.31*	*17.90*	*101.00*	*N/A*
305	*10*	*24.22*	*5.86*	*99.26*	*Insignificant*
324	*7*	*61.91*	*38.32*	*99.00*	*Insignificant*
0326-a[1]	*6*	*35.63*	*12.69*	*97.97*	*Insignificant*
0326-b[1]	*6*	*34.11*	*11.64*	*98.81*	*Insignificant*
0328-1	*8*	*77.55*	*60.14*	*96.60*	*Significant*
0328-2	*7*	*80.69*	*65.11*	*96.73*	*Significant*
0328-3	*7*	*44.46*	*19.77*	*98.15*	*Insignificant*
0328-4	*7*	*87.50*	*76.55*	*96.48*	*Significant*
0328-5	*8*	*44.25*	*19.58*	*98.02*	*Insignificant*
0328-6	*7*	*64.74*	*41.92*	*97.96*	*Insignificant*
0328-7	*8*	*63.96*	*40.90*	*97.85*	*Insignificant*
0328-8	*10*	*70.78*	*50.10*	*97.94*	*Significant*
0328-9	*8*	*93.53*	*87.47*	*97.59*	*Significant*
0328-10	*7*	*80.46*	*64.74*	*98.23*	*Significant*

[1]The monitored project comprised two identical buildings.

[2]A learning rate value of 100% indicates that no learning has taken plane. A value greater than 100% indicates that, in contrast to the learning curve theory principle, actually there is a positive relationship between man-hours and cycle numbers, i.e. man-hours increase as the cycle number increases. In both cases, the learning curve theory is inapplicable to the monitored steel fixing activities of beams.

[3]An insignificant influence of learning on fixing beam reinforcement inputs indicates that, although there is a negative relationship between cycle numbers and labour inputs, i.e. labour inputs decrease as the cycle number increases, its impact has no statistical significance.

9.4.2 Analysis of the Effect of Learning on Reinforcing Steel Productivity of Slab Panels

The labour inputs of fixing reinforcement in recurring slab panels were monitored for further investigation of the applicability of the learning phenomenon to reinforcing steel trade.

Table 9.6 summarises the results of the learning curve investigation for reinforcing steel fixing on all observed recurring slabs. As with beams activity, it can also be noticed from the table that there is an inconsistent pattern of the effect of learning on fixing slab panels reinforcement. Although the influence of learning phenomenon was exhibited in some monitored buildings, others either showed an insignificant decrease or an increase in labour inputs as the floor cycle numbers increased. As shown in table 9.12, from the twenty-one observed buildings, only 19% exhibited significant reduction in labour inputs as a result of repetition. However, the observed buildings in which a significant effect of learning on labour inputs was determined, none of the learning rates fell in the expected range of 70% to 90%. Once again, the quantified Learning rates shown in table 9.6 indicate that either no or little productivity improvement has taken place in the process of fixing reinforcing steel in identical recurring slab panels.

Table 9.6 Results Summary for the Investigation of the Applicability of Learning Curve Theory to Reinforcing Steel Trade – Recurring Slab Panels

Project No.	*Total No. of Observed Cycles*	*Coefficient of Correlation (%R)*	*Coefficient of Determination (% R^2)*	*Learning Rate (S)*[2] *(%)*	*Influence of Learning on Reinforcing Steel Productivity*[3]
0201	5	34.94	12.21	97.78	Insignificant
0203	6	46.91	22.01	98.56	Insignificant
0204	6	47.35	22.42	97.43	Insignificant
0213-a[1]	8	36.00	12.95	98.72	Insignificant
0213-b[1]	8	73.68	54.29	96.38	Significant
0302	11	29.45	8.67	101.00	N/A
0304	4	86.04	74.03	104.70	N/A
0305	10	55.63	30.95	97.85	Insignificant
0324	7	8.39	0.704	100.00	N/A
0326-a[1]	6	73.31	53.75	94.50	Insignificant
0326-b[1]	6	29.82	8.89	98.90	Insignificant
0328-1	8	77.64	60.27	95.15	Insignificant
0328-2	7	73.96	54.70	96.12	Insignificant
0328-3	7	22.67	5.14	99.28	Insignificant
0328-4	7	81.75	66.83	96.23	Significant
0328-5	8	59.21	35.06	97.10	Insignificant
0328-6	7	66.95	44.82	97.95	Insignificant
0328-7	8	83.07	69.00	92.83	Significant
0328-8	10	10.61	1.13	100.00	Insignificant
0328-9	8	78.12	61.02	96.71	Significant
0328-10	7	53.56	28.69	97.10	Insignificant

[1]The monitored project comprised two identical buildings.

[2]A learning rate value of 100% indicates that no learning has taken plane. A value greater than 100% indicates that, in contrast to the learning curve theory principle, actually there is a positive relationship between man-hours and cycle numbers, i.e. man-hours increase as the cycle number increases. In both cases, the learning curve theory is inapplicable to the monitored steel fixing activities of slab panels.

[3]An insignificant influence of learning on fixing slab panels reinforcement inputs indicates that, although there is a negative relationship between cycle numbers and labour inputs, i.e. labour inputs decrease as the cycle number increases, its impact has no statistical significance.

9.5 Analysis of the Effect of Learning on Pumped Concrete

The final investigation phase of the applicability of the learning phenomenon involved pumped concrete trade.

Table 9.7 summarises the results of the learning curve investigation for pumped concrete on all observed recurring floors. It can be seen from the table that for all monitored buildings, a positive relationship exists between concreting labour input and cycle numbers. The cycle number however is directly related to the height of floor above the ground level. As we have previously found in chapter eight, there is a significant negative impact of height on pumped concrete labour productivity. Based on the results obtained in this investigation, we may conclude that; provided the learning phenomenon has a significant positive influence on pumped concrete labour productivity, the negative effect of height is stronger than the effect of learning and overshadows its impact.

Table 9.7 Results Summary for the Investigation of the Applicability of Learning Curve Theory to Pumped Concrete – Recurring Floors

Project No.	Total No. of Observed Cycles	Coefficient of Correlation (%R)	Coefficient of Determination (%R²)	Learning Rate (S)[2] (%)	Influence of Learning on Pumped Concrete Productivity
0201	4	70.31	49.43	104.70	N/A
0203	6	63.47	40.29	103.30	N/A
0204	6	68.52	46.94	104.00	N/A
0213-a[1]	6	48.02	23.05	102.90	N/A
0213-b[1]	6	57.57	33.14	102.50	N/A
0302	6	63.71	40.59	104.20	N/A
0304	5	74.03	54.80	109.40	N/A
0305	6	71.84	51.61	103.60	N/A
0324	7	77.43	59.96	108.40	N/A
0326-a[1]	6	90.36	81.64	109.50	N/A
0326-b[1]	6	77.53	60.11	105.70	N/A
0328-1	8	34.96	12.22	102.20	N/A
0328-2	7	91.35	83.45	114.50	N/A
0328-3	7	67.02	44.91	104.70	N/A
0328-4	7	81.01	65.63	107.60	N/A
0328-5	8	79.20	62.71	105.50	N/A
0328-6	7	77.11	59.45	105.00	N/A
0328-7	8	79.14	62.63	105.00	N/A
0328-8	10	83.98	70.53	109.20	N/A
0328-9	8	46.93	22.02	102.20	N/A
0328-10	7	92.03	84.69	109.60	N/A

[1]The monitored project comprised two identical buildings.

[2]A learning rate value of 100% indicates that no learning has taken plane. A value greater than 100%, indicates that, in contrast to the learning curve theory principle, actually there is a positive relationship between man-hours and cycle numbers, i.e. man-hours increase as the cycle number increases. In both cases, the learning curve theory is inapplicable to the monitored concreted floor.

9.6 Summary

An investigation into the applicability of learning curve theory, using the unit straight-line model, was conducted on the formwork, reinforcing steel fixing and pumped concrete trades. Multi-storey buildings having identical recurring floors were selected for this investigation. The impact on labour productivity due to learning was quantified by investigating the change in labour inputs as the cycle number increased within the observed buildings.

According to the learning curve theory, we would expect the labour inputs to decrease as the cycle number increases. However, formwork activities observed exhibited either insignificant improvements, or on the contrary, an increase in labour inputs as the cycle number increased. Moreover, Reinforcing steel trades, i.e. fixing reinforcement in beams and slab panels, exhibited sporadic patterns. Whilst the influence of learning phenomenon was exhibited in some monitored buildings, others, as with the case of formwork, either showed an insignificant reduction in labour inputs, or in contrast to the theory, an increase in labour inputs was associated with the increased number of floor cycles.

On the other hand, due to the significant negative impact of height on pumped concrete productivity, the effect of learning could not be determined. In fact, all monitored buildings showed a consistent increase in labour inputs as the number of floors increased. Therefore, we may reasonably conclude that even if the learning phenomenon does have a positive influence on pumped concrete productivity, its effect is masked and overshadowed by the negative impact of height above ground level of floors within the monitored buildings.

The outcome of this investigation on *in situ* reinforced concrete construction indicates that there is no potential context for the learning curve theory to be used as a useful tool to quantify the productivity improvement, or to provide for a practical project management observation and control.

Chapter Ten

Discussion of Results

10.1 Introduction

There are few published quantitative results which can be compared with the findings of this research project. However, such data as exist have been examined and discussed.

The main objectives of this chapter are to discuss and compare the findings of this study with previous research, correlate them with the existing body of basic buildability principles presented in chapter two, namely, design rationalisation, standardisation and repetition, and highlight their practical implementations within the *in situ* reinforced concrete construction industry.

10.2 Formwork

The influence of buildability factors on labour productivity has been the subject of several research projects [4,17,21,25,34,40,41,50,74,78,115]. However, few were able to quantify such an influence in practical terms. Most of the reviewed literature introduced general design guidelines and recommendations based on the potential influence of various variables on formwork labour productivity.

Smith and Hanna [99] discussed similar buildability factors hypothesised to influence formwork labour productivity to those investigated in this research. Such factors included consistency, simplicity, standardisation and repetition of elements. The results of this study not only confirmed such hypotheses, but also quantified their impacts on formwork labour productivity of major activities and elements of buildings. In analysing the influence of intersections, i.e. corners, on formwork productivity of walls, Smith and Hanna compared the productivity of straight walls to those with intersections, and an average loss of approximately 48% in formwork productivity was quantified between the two categories due to the presence of such intersections.

Furthermore, Smith *et al* [100] in their investigation of factors affecting formwork productivity of vertical members, reported a substantial loss of productivity ranging in ratio from 1.10 to 2.00 in comparison with straight walls base rate due to the presence of corners in wall perimeters, which further confirmed the results obtained by Smith and Hanna [99].

In this research project, a broader approach yet, similar in concept was used to examine the influence of perimeter geometry on formwork labour productivity of walls and extended to cover the same concept in other elements such as raft foundations, ground slabs and floor edges. The overall pattern of the results obtained is in agreement with previous findings; holding the shutter area of the observed elements constant, as the ratio of the total number of angles around the perimeter to the total length of the perimeter increases by one unit, formwork labour productivity significantly decreases, on average, by 4.62, 1.13 and 0.250 m^2/mh for raft foundations, slab edges and walls respectively.

O'Connor *et al* [81] as well as Alshawi and Underwood [8] discussed the negative effect of the variability of element sizes and the influence of grid patterns on the complexity of the construction process. However, their work was limited to general guidelines without any quantification of the impact of such factors on the construction productivity. Our work revealed that although the variability of element sizes negatively influences the formwork labour productivity of the activity, its effect on most activities observed was statistically insignificant. On the other hand, the investigation of grid pattern on setting-out isolated foundations and columns labour productivity revealed a consistent pattern for both activities; as the ratio of the total number of elements to the total number of axes increases by one unit, the labour productivity significantly increases, on average, by 1.56 and 1.97 footings/mh and columns/mh for isolated foundations and columns respectively. This finding further confirms the complexity associated with setting-out scattered and irregular versus uniform and symmetrical grids.

Fisher and Tatum [34] discussed the negative impact of circular columns on formwork productivity. Once again, their work comprised design guidelines and recommendations geared towards constructability knowledge and improvement. In this research, the influence of the presence of circular columns was assessed at the macro-level, and the average difference in labour productivity between shuttering circular and rectangular columns was also quantified at the micro-level. Holding all other factors influencing labour productivity constant, as the percentage of circular columns in floors increases by one unit, the macro-level labour productivity significantly decreases by an average of 0.0124 m^2/mh. On the other hand, an average loss in micro-level labour productivity of 29% compared with shuttering rectangular columns was associated with shuttering circular columns.

The presence of dropped beams in floors and its effect on labour productivity was discussed by the Buildable Design Appraisal System [21], where a set of labour saving indices is suggested to account for the presence and arrangement of beams in floors. The higher the index, the more efficient the labour usage and therefore the higher the site labour productivity. Labour saving indices for *in situ* reinforced concrete construction range in magnitude from 0.4 to 3.0. To account for the negative influence of the presence of beams, the suggested indices for beam-slab floors range from 0.5 to 0.7 depending on: a) whether such floors include one or two-directional beams; and b) the "Slab/Beam Ratio", which is defined as the number of beams used to support the floor area. In this study, the effect of beams on formwork labour productivity of floors was assessed at the macro-level, and the result is in accordance with the impact suggested by the appraisal system. However, in our work, a slightly different approach from that of the BDAS was taken to quantify the effect of dropped beams on labour productivity. The BDAS quantifies the influence of beams by introducing the "Slab/Beam Ratio", which basically accounts for the number of beams used to support a certain floor area regardless of the dimensions of such beams. In addition, according to the BDAS concept, this factor can only be used with beam-slab construction. In our research, a more generic approach was adopted by including the impact of the total area of beams formwork used to support the monitored floors. The total sum of formwork areas of beams, i.e. m^2, was then divided by the total area supported by these beams. The overall factor was called the "Beam-Floor Ratio", and was used to investigate the influence of the presence of dropped beams on the labour productivity of floors. This approach proved useful to investigate the effect of beams taking into account also the influence of formwork areas. In addition, this factor simply drops to zero when the observed floor is of the flat plate type, i.e. beamless. The quantified result indicated a significant negative relationship between the "Beam-Floor Ratio" and formwork labour productivity; holding all other factors influencing formwork labour productivity of floors constant, a unit increase in the "Beam-Floor Ratio", causes a significant average loss of 1.72 m^2/mh in macro-level labour productivity.

The influence of span geometry of beams was also investigated. Previous research [32,100] attributed poor buildability to curved forms. The quantified influence of such forms further confirmed this concept. Holding all other factors influencing labour productivity constant, as the percentage of curved beams in the observed floors increases by one unit, macro-level labour productivity significantly decreases by an average of 0.0209 m^2/mh. On the other hand, and in comparison with linear beams, for first and repeated erected curved beams formwork respectively, the average losses of 88% and 84% in micro-level labour productivity were quantified.

The effect of formwork interruption in beams was revealed by investigating the impact of beam intersections on labour productivity. The outcome of this investigation indicated a significant negative relationship between the number of intersections formed in beams and the labour productivity holding all other factors affecting this activity constant. In forming ground beams, average labour productivity losses of 0.0203 and 0.0987 m^2/mh for each unit increase in the number of beam intersections were quantified for macro and micro-level formwork labour productivity respectively. Furthermore, in forming suspended floor beams, for each unit increase in the number of such intersections, the quantified average macro and micro-level labour productivity losses were 0.0117 and 0.305 m^2/mh respectively. Even though the author could not identify relevant previous research concerning this finding, the result falls within the standardisation concept advocated for in previous constructability research projects [25,34,81].

Standardising floor layout modules minimises waste of forming materials and therefore enhances the constructability of projects [34]. This concept was proven in this research by quantifying the average loss in labour productivity associated with forming irregular shaped slab panels in floors. Holding all other factors influencing the labour productivity constant, as the percentage of non-rectangular floor panels in floors increases by one unit, macro-level labour productivity significantly decreases by an average of 0.00700 m^2/mh. At the micro-level investigation, in comparison with rectangular floor panels, an average loss of 35% was observed with first erected non-rectangular panels, whereas 23% loss in labour productivity was observed in repeated panels.

Numerous research projects and literature discussed the importance and positive influence of repetition on productivity [24,25,32,34,73,81]. In this study, the effect of material repetition on formwork labour productivity was quantified for building floors and various elements such as columns, beams and slab panels. On the one hand, an average gain in macro-level labour productivity of 21% was quantified in repeated building floors, and on the other, an average gain of 7% was realised in macro-level labour productivity of repeated shuttered columns. Moreover, the impact of repetition was also significant in floor beams. Whilst an average gain of 21% in micro-level labour productivity was achieved in linear beams due to forms repetition, on average, 63% gain in labour productivity was observed in curved beams. Consistent with the pattern of the results obtained for beams, an average gain in labour productivity of 8% was achieved in rectangular slabs whereas, an average gain of 29% was observed in non-rectangular slab panels. The quantified results reveal the importance of forms repetition on labour productivity, especially in curved and irregular shaped elements, i.e. curved beams and non-rectangular slab panels.

10.3 Reinforcing Steel

Apart from the introduction of general hypotheses on the potential influence of buildability factors on labour productivity of reinforcing steel fixing [76], and the investigation of the impact of planning, delivery and material management on the productivity of the overall activity, except for the attempts conducted by Aldana and Hidayatalla [4,50], the author could not identify relevant literature which quantified the impact of buildability factors on reinforcing steel fixing labour productivity to be compared with the results obtained from this study.

Aldana [4] concluded a positive relationship between reinforcing steel bar diameters and fixing labour productivity. In addition, the quantified fixing labour productivity was different for different members. Hidayatalla [50] concluded three main findings: a) labour productivity of reinforcing steel fixing is different in different elements; b) a positive relationship between labour productivity and bar diameters exists, which further confirmed Aldana's findings; and c) labour productivity is adversely affected by high steel content. Hidayatalla quantified an average increase in fixing labour productivity of 2.51 kg/mh and 19.43 kg/mh in slabs and walls respectively as the rebar diameter increases by 1.00 mm. In addition, his work revealed an average loss of 1.11 kg/mh in labour productivity as the steel content increases by 1.00 kg/m^3 in bases and slabs. However, it is important to note that other factors which also affect the labour productivity of fixing reinforcing steel bars in bases, slab panels and walls, e.g. geometry of bases and slab panels, wall thickness and the quantity of reinforcement fixed in walls, were not included in the models.

Our work further confirmed the first finding. However, the average rates of labour productivity in bases, slab panels and walls as the rebar diameter increases by 1.00 mm, taking into account the effect of geometry of bases and slab panels, wall thickness and the quantity of reinforcement fixed in walls, were 7.43, 11.79 and 2.02 kg/mh respectively. Moreover, in contrast to the third finding, the outcome of this study quantified a significant positive relationship between the quantity of reinforcement fixed and labour productivity. Our work quantified an average increase in labour productivity rates of 0.000492 and 0.000953 kg/mh as the quantity of reinforcement fixed increases by 1.00 kg in bases and slab panels respectively. This pattern was consistent at both observation levels, macro and micro, and amongst all observed activities and elements. It is important to note however, that the previous research projects conducted by Aldana and Hidayatalla were of short duration and consisted of few data points; hardly the basis for sound and reliable conclusions.

Whilst the negative influence of variability of foundation sizes was not statistically significant, column and beam activities showed a significant negative relationship between steel fixing labour productivity and the variability of sizes. Holding all other factors impacting fixing labour productivity constant, a unit increase in the total number of different element sizes causes, on average, a loss of 0.638 and 0.341 kg/mh in labour productivity of columns and beams respectively. Although no previous research could be identified to compare this finding with, the outcome of this investigation fits within the overall concept of design rationalisation [73].

The importance of standardisation [24,73] was confirmed by quantifying the influence of elements' geometry on steel fixing labour productivity. The effect of geometry was investigated in columns, beams and slabs, and a consistent pattern was realised. Columns observed at the macro-level were associated with a significant reduction in labour productivity as the percentage of reinforcement fixed in circular columns increased. On average, and holding all other factors influencing labour productivity constant, as the percentage of reinforcement quantity fixed in circular columns increases by one unit, labour productivity significantly decreases by 0.289 kg/mh. Moreover, compared to rectangular columns, an average significant loss of 38% in micro-level labour productivity was associated with fixing reinforcement in circular columns.

On the other hand, macro-level observation of beams revealed a significant negative relationship between labour productivity and the percentage of reinforcement fixed in curved beams. On average, as the percentage of curved beams in floor increases by one unit, labour productivity significantly decreases by 0.391 kg/mh, holding all other factors constant. Furthermore, curved beams observed at the micro-level were accompanied by an average significant loss in labour productivity of 38% compared to linear beams.

The impact of slab geometry on fixing reinforcing steel bars in base and flat slabs was quantified. Holding all other factors impacting labour productivity constant, on average, a significant loss of 15% was associated with fixing reinforcement in non-rectangular relative to rectangular slabs. This pattern was also consistent amongst individual non-rectangular slab panels observed at both levels, macro and micro. Fixing reinforcement in slab panels observed at the macro-level was associated with a significant reduction in labour productivity of 0.484 kg/mh as the percentage of reinforcement quantity fixed in non-rectangular panels increases by one unit. At the micro-level observation, a significant average loss of 38% in fixing labour productivity was quantified in comparison with rectangular slab panels.

The importance of applying the buildability concept [23] was also revealed through the investigation of the effect of wall thickness on steel fixing labour productivity. Fixing reinforcing steel bars in narrow walls is associated with difficulties and a loss in productivity. This study determined a significant positive relationship between wall thickness and steel fixing labour productivity; increasing the wall thickness by 1.00 mm, yields, on average, a significant increase of 0.411 kg/mh in labour productivity. Adequate space should be provided for fixers to perform the activity efficiently whilst maintaining, as much as practical, the concept of engineering economy.

Fisher and Tatum [34] identified critical design variables which are important for the constructability of structures. Such variables included dimensions of elements, e.g. width, depth and length, quantity, type and location of reinforcement. However, in their research, the impacts of such variables upon the construction process were not quantified. In this study, the effects of such buildability factors on labour productivity were investigated and quantified. The dimensions of elements have a significant impact on steel fixing labour productivity. Beams investigated at both macro and micro levels, revealed a significant negative influence of width and depth on labour productivity. Deep beams were consistently associated with lower labour productivity. Holding all other factors impacting the labour productivity of this activity constant, macro-level observation of beams revealed an average loss of 0.0500 kg/mh in labour productivity for each 1.00 mm increase in beam depth. In addition, wide beams, which usually involve fixing multi-leg stirrups, were associated with an average reduction in macro-level labour productivity of 0.0363 kg/mh for each 1.00 mm increase in beam width. This pattern was also realised in beams observed at the micro-level. Whilst an average loss of 0.00832 kg/mh in labour productivity was quantified for each 1.00 mm increase in beam depth, on average, a loss of 0.0515 kg/mh was associated with increasing the beam width by 1.00 mm, holding all other relevant factors constant.

Due to the complexity associated with the mechanism of fixing large diameter stirrups in beams, an average loss of 10% in macro-level labour productivity was quantified as a result of fixing 10 mm stirrups in diameter in comparison with 8 mm stirrups.

The influence of reinforcement location in base, flat and individual slab panels was also quantified. Commonly, thin slabs are singly reinforced whereas thick slabs normally require double layers of reinforcement, i.e. bottom and top. Although specifying reinforcement in double layers in thick slabs, i.e. thickness greater than or equal to 250 mm, is a detail requirement usually designers have little control over, quantifying the effect of reinforcement location on fixing labour productivity would provide constructors with a tool for allocating resources, estimating activity duration and cost control. On average, labour productivity losses associated with fixing top layer reinforcement in rectangular and non-rectangular base and flat slabs were 15% and 13% in comparison with bottom layer respectively. However, the pattern was not consistent, and an opposite result was realised in individual slab panels. For rectangular slabs, fixing the top reinforcement layer was associated with an average of 20% increase in labour productivity in comparison with fixing the bottom layer, whereas, an average increase of 63% in labour productivity was associated with fixing the top reinforcement layer compared to the bottom layer of non-rectangular slabs. However, the average values of the characteristic bar diameter and quantity of reinforcement fixed in the top reinforcement layers of slab panels, compared with base and suspended flat slabs, were substantially larger than those fixed in bottom layers. Thus, we may reasonably conclude that the effects of reinforcing steel bar diameter and quantity of reinforcement on labour productivity are more influential than the impact of layer location and overshadow its effect.

10.4 Concreting

Factors influencing the labour productivity of pumped and skipped concrete were investigated and quantified. Common buildability factors affecting pouring labour productivity for the two placement methods included volume, concrete workability, steel congestion and height above ground level.

Observation of skipped concrete was limited to vertical members, i.e. columns and walls, whereas pumped concrete was monitored in all other concreting activities. Due to the difference between the elements cast by the two different placement methods, i.e. shape factor, a meaningful comparison between skipped and pumped concrete is not possible [11]. Consequently, separate analyses were conducted on the two placement methods to quantify the impacts of buildability factors on the labour productivity of the process.

For both placement methods, the outcome of this study revealed a significant positive relationship between labour productivity and volume placed. Anson and Wang [11] concluded a similar pattern. However, the impact of other factors influencing concreting labour productivity, e.g. workability and steel congestion, were not included in their analysis. For all pours, except tremied concrete, Anson and Wang quantified an average increase of 0.11 m^3/h as the volume of concrete increases by 1.00 m^3. However, such relationship quantifies the placing speed and not the labour productivity versus the volume placed.

Our finding reveals that, holding all other factors influencing the labour productivity of the activity constant, on average, the labour productivity of pumped and skipped concrete increases by 0.00322 and 0.00618 m^3/mh for each 1.00 m^3 increase in concrete volume respectively. Even though a direct comparison between our finding and that of Anson and Wang is not possible due to the difference in measurement units, i.e. m^3/h versus m^3/mh, the pattern of the two findings seems to agree.

The effect of concrete workability on casting labour productivity was also significant. For both placement methods, a significant gain in labour productivity was associated with high slump mix. High workability of concrete has the advantages of permitting easy and quick placement [90]. An average percentage loss of 23% in labour productivity was observed as a result of pumping medium concrete workability relative to the high category. A consistent pattern in productivity loss was also determined for skipped concrete between placing high and medium workability mix. However, due to the difference in the casting mechanism between the two placement methods, the quantified difference in average productivity loss between placing medium relative to the high workability mix was higher at

30%. Moreover, the average percentage gain in labour productivity due to placing medium workability concrete, in comparison with low workability, was significant at 59% for pumped versus 58% for skipped concrete. Furthermore, an average percentage difference of 108% gain in labour productivity was associated with pumping high relative to low workability mix, whilst a difference of 125% between the two categories was quantified for skipped concrete.

Although the author could not identify relevant research to compare the pattern of this finding with, the results obtained in this study fall within the overall concept of design simplification and in accordance with the general recommendation for concrete workability provided by the National Research Council of Canada [90].

High steel content results in congestion which could lead to added difficulty in placing concrete. In our research, a significant negative relationship was determined between concreting labour productivity and high steel content. Furthermore, the pattern was consistent in both placement methods; pumped and skipped concrete. Holding all other factors affecting the labour productivity of this activity constant, increasing the steel congestion ratio by one unit, causes an average loss of 0.00181 and 0.000956 m^3/mh in pumped and skipped concrete labour productivity respectively. Although similar previous research could not be identified, the result correlates with the overall buildability concept [23].

Anson and Wang [11] also investigated the influence of height above ground level on concreting labour productivity, and found no effect of height on pumped, and surprisingly, on skipped pours. However, they concluded that the height effect on skipped concrete must have been masked by other factors. It is the author's opinion that such factors may have been excessive congestion of reinforcement, low slump mix and/or delays encountered which might have overshadowed the influence of height. In contrast to their finding, a significant negative impact of height on both pumped and skipped concrete labour productivity was found in this study. Our work quantified an average loss of 0.0238 and 0.00834 m^3/mh associated with every 1.00 m increase in height above the ground level for pumped and skipped concrete labour productivity respectively. This finding further confirms the conclusion hypothesised by Anson and Wang.

10.5 Power-Trowelled Concrete Surface Finish

Two major factors influencing power-trowelling productivity were identified: a) area of trowelled floor; and b) the number of machines used in the activity. Although the later variable is not a buildability factor, its impact was revealed. Whilst a significant positive relationship between trowelling productivity and area of floor was determined, a negative effect of the number of machines used in the process was realised. Holding the number of trowelling machines used in the activity constant, as the floor area increases by 1.00 m^2, the trowelling productivity increases, on average, by 0.0469 m^2/mh. On the other hand, for each added trowelling machine, and holding the floor area constant, an average loss of 9.13 m^2/mh in trowelling productivity is realised. Notwithstanding that the researcher could not identify similar previous research to compare these findings with, the results are in agreement with the economy of scale concept on the one hand, and the overcrowding influence on the other. As was previously indicated in chapter eight, a labour density greater than one man per 30 m^2 would lead to decrease in productivity [60]. This finding was further corroborated by this research project.

As we have previously indicated, this finding also suggests that for a given floor area, there is an optimum number of machines to be utilised in order to maximise the trowelling productivity. Quantifying this optimum number should be a subject of future investigation.

10.6 The Applicability of Learning Curve Theory to Reinforced Concrete Construction

Several previous research [25,28,30,110,111] investigated the effect of learning on construction productivity and found a positive correlation between productivity and the recurring cycle number. In the case of core walls investigated by Touran *et al* [111], the average productivity rate in formwork construction in floors 1 to 8 improved by 40% compared to the first floor, and in floors 9 to 15 improved by 47% compared to floor 9. Dong [25], analysed the effect of repetition on the overall labour productivity of 18 housing projects and found a significant positive linear relationship between repetition and labour productivity.

In this study, the influence of learning on formwork, reinforcing steel fixing and pumped concrete labour productivity of floors was examined and sporadic results were obtained. In contrast to previous research findings, none of the recurring floors in monitored buildings exhibited significant learning effect on formwork labour productivity.

Although the author could not identify previous research on the impact of learning on reinforcing steel fixing productivity, again, inconsistent results were obtained in this trade. Whilst the effect of learning on labour productivity was exhibited in few monitored buildings, the majority showed insignificant influence.

The effect of the learning phenomenon on pumped concrete labour productivity could not be determined. If it exists however, its influence has been overshadowed by the negative impact of height. In all monitored buildings, the outcome of this investigation showed consistent decrease in labour productivity associated with the recurring cycle number, i.e. increase in man-hours as the floor height increases for the same volume of pumped concrete.

The inapplicability of the learning phenomenon to labour productivity of *in situ* reinforced concrete construction may be attributed to three reasons. First, gang members distribute work tasks amongst themselves according to floor areas, and despite the fact that the same gang members perform the activity within the single as well as recurring floors, there is no guarantee that the same gang members would be performing the same tasks amongst the building floors. Single floors within the monitored buildings included various beam and slab panel sizes, and when labours perform certain tasks in one floor, it does not necessarily indicate or mean that the same labours would conduct the same tasks in the following floors. However, as the number of stories within the monitored buildings increases, we may reasonably assume that the chances of the same labours encountering the same tasks increase markedly which may allow for the learning phenomenon to exhibit itself. In view of the previous discussion, the second reason may be attributed to the relatively low number of floors within the monitored buildings which were available at the period of the data collection and therefore selected for this investigation. Finally, the inapplicability of the learning phenomenon may be due to a psychological effect. Once the first few cycles within a multi-storey building are concluded, e.g. the first two or three floors, the elapsed period would be subconsciously targeted and expected by labours for the following floors. Consequently, and even if some saving in inputs is achieved due to learning, labours might still use the overall expected period by either reducing their work pace, or taking more frequent breaks.

10.7 Practical Implementations of Main Findings to the Reinforced Concrete Construction Industry

The findings of this research project include specific buildability knowledge and its influence upon the labour productivity of major reinforced concrete trades. Based on the quantified results presented in chapters six, seven, eight and nine, which were also discussed in the previous sections of this chapter, the basic buildability principles previously introduced in chapter two, i.e. design rationalisation, standardisation and repetition, can be further classified according to their application in the design stage into the following main categories of buildability knowledge [34]:

a) layout knowledge;

b) dimensioning knowledge;

c) detailing knowledge; and

d) exogenous knowledge

Layout buildability knowledge constrains the horizontal and vertical layout of elements, e.g. grid pattern, geometry of spans, elements and framing systems, height of floors and repetition. Dimensioning knowledge constrains the dimensions of elements, e.g. beam depth and width, wall thickness, panel areas, depth of slabs and concrete volume. Detailing knowledge impacts the detailed design of elements, such as quantity, diameters, location and layout of reinforcement, and concrete workability. It is important to note however, that detailing requirements are often a direct consequence of layout and dimensioning decisions. Exogenous buildability knowledge on the other hand, pertains to construction methods and management decisions which are beyond the control of the designer, e.g. selected concrete placement method and number of trowelling machines used, but can be controlled by the site management.

Practical recommendations and guidelines for buildability improvement are presented for each activity observed. However, as a general rule, since some recommendations, when implemented, may result in material increase, e.g. forms, reinforcement and/or concrete, designers should carefully evaluate the cost/benefit ratio before deciding on a specific option.

10.7.1 Design Guidelines for Formwork and Reinforcing Steel Activities

A. Isolated Foundations

Since formwork labour productivity is positively influenced by the shutter area of isolated foundations, especially the average shutter area, structural designers should consider, as far as practical, the option of combined foundations, e.g. lumping several columns in close proximity to one another onto a single foundation. This dimensioning knowledge, if implemented, will result in overall fewer foundations and maximises the average shutter area, a factor which has the largest positive influence on labour productivity. Moreover, this option might, to a lesser extent, facilitate ease of construction by minimising the variability of foundation sizes within the activity. On the other hand, reinforcing steel fixing labour productivity can be improved through the detailed knowledge of the effect of bar diameter on labour productivity. For the same required area of reinforcement, designers should consider the option of specifying large bar diameters. For instance, if the required area of steel is 2400 mm^2, instead of specifying 12 bars 16 mm in diameter, 8 bars 20 mm in diameter can be specified and will provide approximately the same area.

B. Base and Suspended Flat Slabs

The procedure of fixing edge formwork is basically the same for base slabs, i.e. raft foundations and ground slabs, and suspended flat slabs. The formwork labour productivity of this activity is largely influenced by the geometry of the formed edges. Design guidelines which enhance the formwork labour productivity largely depend upon the location of the element. In raft foundations, the structural designer, to a large extent, is at liberty to control the geometry of the perimeter since such elements are usually embedded. On the other hand, the geometry of ground and floor edge perimeters is governed by the architectural concept. In both cases however, it is recommended that architects and structural designers, whenever possible, opt for rectangular geometry, otherwise, minimise the number of angles around the perimeters. Such a layout, when implemented, would not only increase the efficiency of the activity, but also positively influences the reinforcing steel fixing labour productivity by minimising the variability of bar lengths within the stacked reinforcement. In addition, as is the case with isolated foundations, specifying large bar diameters would significantly increase steel fixing labour productivity.

C. Columns

To improve formwork and steel fixing labour productivity of columns, architects should keep circular sections to a minimum. Furthermore, since the formwork labour productivity of columns is largely influenced by the average shutter area, whenever possible, two or three columns, within short distances from one another, may be substituted by a single large column. This may also reduce the variability of column sizes within the building. Moreover, reinforcing steel fixing labour productivity can be improved by specifying large bar diameters as we have previously illustrated.

Another important factor affecting the labour productivity of this activity is the grid pattern. It is recommended that architects, as far as possible, distribute the columns within the building both symmetrically and regularly to achieve better buildability and labour productivity not only in column activities, but also in isolated foundations.

In addition, the influence of repetition should be taken advantage of. It is recommended that designers keep column sizes within the building floors constant and change the amount of reinforcement whenever needed. Applying such layout and dimensioning knowledge into the design stage will translate into significant savings in labour inputs and efficient operations.

D. Walls

Since shutter area of walls has the strongest impact on formwork labour productivity, it is recommended that this dimensioning knowledge be applied by substituting several collinear short walls, when possible, by a single wall. In addition, architects are advised to apply the layout knowledge of wall geometry by using straight segments whenever possible, and when the design requirements necessitate otherwise, keeping the geometry of walls simple with a minimum number of angles around the perimeter. Furthermore, as is the case with columns, the effect of repetition should be also utilised in walls. Designers should keep wall sizes constant within building floors and change the amount of reinforcement as required.

Enhancing reinforcing steel fixing labour productivity of walls can be achieved by implementing the following dimensioning and detailing knowledge: a) ensuring sufficient space for fixers by providing an adequate wall thickness; and b) specifying large bar diameters for the required area of reinforcement.

E. Suspended Floors

The type of framing system selected by the structural designer largely influences formwork labour productivity of suspended floors. To ensure an efficient operation, structural designers should apply this layout buildability knowledge and consider flat plates, i.e. beamless floors, as a first framing option. When such framing system is impractical, dimensioning buildability knowledge suggests that beams used to support the floor should be kept to a minimum, both in number and dimensions, i.e. width and depth. In addition, to minimise forming joints at beam intersections, beams should be framed onto columns and walls. On the other hand, architects should avoid, or keep to a minimum, curved and/or irregular plans which might lead to curved beams and/or non-rectangular slab panels.

Furthermore, the repetition of the floor layout, both architecturally and structurally, should be maximised in order to enhance formwork labour productivity.

Specifying large bar diameters for the main reinforcement of beams and slabs, keeping the beam stirrup diameters to a minimum practical size, and minimising the variability of beam sizes in the floor, together with the previously recommended layout and dimensioning knowledge, would significantly increase the formwork and reinforcing steel fixing labour productivity of this activity.

10.7.2 Design & Management Control Guidelines for Concreting and Trowelling Trades

In this section, the recommendations and guidelines for enhancing the buildability and labour productivity of concreting and trowelling trades are classified into two categories: a) design; and b) site management control. Design guidelines pertain to practical recommendations to be considered by designers, whereas, management control is related to decisions which are beyond the control of the designers, i.e. exogenous knowledge, but which can be controlled by the site management. Design recommendations to enhance concreting labour productivity include making effective use of the detailing buildability knowledge. High to medium concrete workability should be specified, especially when members contain a large quantity of reinforcement. A low workability mix slows down the operation, significantly reduces the labour productivity, and may lead to honeycombing. On the other hand, when a power-trowelled surface finish is specified, designers should take advantage of the positive relationship between trowelling productivity and floor area. Maximising the trowelled floor area, as far as practical, leads to higher finishing productivity and more efficient use of the trowelling machines.

Practical recommendations are also extended to site management to utilise the dimensioning and layout knowledge deduced from this research to improve the efficiency of the operation, and provide for better planning, scheduling and cost control. Concreting activities should be scheduled in such a way as to maximise the volume of pours, i.e. small volume pours should be avoided as much as possible. Furthermore, planning for concrete pours above ground level should take into consideration the significant reduction in labour productivity as a result of height, and its consequences on the operation's resources, i.e. man-hours and cost.

Another important factor which is worth considering by the site management is that increasing the number of trowelling machines does not necessarily enhance the productivity of the trowelling operation. In fact, this research determined a negative relationship between trowelling productivity and the number of machines used. Therefore, until further research quantifies the optimum numbers of machines relative to floor areas, site management personnel are encouraged to monitor and keep records of this exogenous factor in order to avoid possible over-manning and, to a large extent, efficiently manage the operation.

It is worth noting that, although it is beyond the scope of this research to test the consequences of practically applying the suggested guidelines and recommendations for buildability improvement in the design environment, in a preliminary pilot test, and with the consent of the design manager, the researcher applied these recommendations to the architectural and structural design disciplines of two different low-rise *in situ* reinforced concrete residential buildings. Each of the appointed constructors was then asked to re-tender for the construction of the building frame but, based upon the modified drawings which incorporated most of the previously highlighted recommendations for buildability improvement. On average, 15% reduction in labour costs was achieved as a result of implementing these recommendations. However, since some of the modifications involved altering a major part of the design concepts and lay-outs, which had been already approved by the clients during the conceptual phase of the design, the construction proceeded according to the initial designs, which reinforces the importance of applying the basic buildability principles during the early stage of the design process.

Notwithstanding that the application of the highlighted design recommendations on two case studies is hardly the basis for a reliable conclusion of their influence on labour productivity, the preliminary results indicate that the implementation of these recommendations during the early stage of the design phase of a project has the potential to a) significantly enhance the construction labour productivity; and b) provide the client with better value for money.

10.8 Summary

Except for the findings of the applicability of learning curve theory to *in situ* reinforced concrete construction, the results of this research project seem to agree reasonably with those of other researchers. The basic buildability principles were investigated and their impacts on labour productivity of the relevant trades were quantified. This study revealed a strong relationship between partial buildability factors, i.e. architectural and structural, and labour productivity, and determined the relative influence of such factors on the labour productivity of the activities and elements observed.

The practical implementation of the main findings of this research was introduced in the form of guidelines and recommendations to be applied during the design stage and, when applicable, the construction phase. In order to facilitate their accessibility and make them readily available to designers and constructors, the information is compiled in Tables 10.1 and 10.2 according to the relevant trades and activities. It is important to note however that whilst such guidelines and recommendations were supported by tangible consequences on the labour productivity, the unique impacts of the buildability factors presented in the tables are to be interpreted only within the corresponding model context. References indicating the numbers of the relevant models, as they appear in the text, are highlighted, and the recommendations for buildability and labour productivity improvements are summarised and presented as follows:

Table 10.1 Design Guidelines for Buildability and Productivity Improvements

Activity	***Recommendation(s)***	***Impact on Macro-Level Labour Productivity***	***Impact on Micro-Level Labour Productivity***	***Reference(s)***
Axes Lay-out	▪ *Distribute columns regularly and symmetrically to achieve regular and symmetrical grid pattern in columns and isolated foundations*	*0.64 foundations/mh and 0.44 columns/mh average gains in labour productivity of isolated foundations and columns setting-out axes respectively as the ratio of the number of foundations and columns to the number of foundations and column axes increase by one unit*	*1.56 foundations/mh and 1.97 columns/mh average gains in labour productivity as the ratio of the number of foundations and columns to the number of foundations and column axes increase by one unit*	*Eqs. 6.1, 6.2, 6.10 and 6.11*
Isolated Foundations	▪ *Where possible, lump several isolated foundations in close proximity to one another into a single combined foundation*	*0.35 m²/mh and 0.0071 m²/mh average gains in formwork labour productivity as the average and total shutter areas of foundations increase by one square metre*	*0.95 m²/mh average gain in formwork labour productivity as the shutter area of an individual foundation increases by one square metre*	*Eqs. 6.2 and 6.3*
		0.0046 kg/mh average gain in fixing labour productivity as the total quantity of reinforcement fixed increases by one kilogram	*0.095 kg/mh average gain in rebar fixing labour productivity as the quantity of reinforcement fixed in an individual foundation increases by one kilogram*	*Eqs. 7.1 and 7.2*
	▪ [1]*Minimise the variability of foundation sizes*	*0.0089 m²/mh average loss in formwork labour productivity as the total number of different foundation sizes increases by one unit*		*Eq. 6.2*
		0.65 kg/mh average loss in rebar fixing labour productivity as the total number of different sizes of foundations increases by one unit		*Eq. 7.1*

[1]*Although the impact of this buildability factor is not statistically significant, applying the recommendation stated in the table would further improve the labour productivity of the activity.*

Table 10.1 Design Guidelines for Buildability and Productivity Improvements (cont'd)

Activity	***Recommendation(s)***	***Impact on Macro-Level Labour Productivity***	***Impact on Micro-Level Labour Productivity***	***Reference(s)***
Isolated Foundations (cont'd)	▪ *Specify large rebar diameter*	*10.83 kg/mh average gain in fixing labour productivity as the rebar diameter increases by one millimetre*	*16.15 kg/mh average gain in fixing labour productivity as the rebar diameter increases by one millimetre*	*Eqs. 7.1 and 7.2*
Ground Beams	▪ *Minimise beam intersections*	*0.020 m^2/mh average loss in formwork labour productivity as the total number of beam intersections increases by one unit*	*0.098 m^2/mh average loss in formwork labour productivity as the number of beam intersections increases by one unit*	*Eqs. 6.7 and 6.8*
	▪ [1]*Minimise the variability of ground beam sizes*	*0.0029 m^2/mh average loss in formwork labour productivity as the total number of different beam sizes increases by one unit*		*Eq. 6.7*
Base and Suspended Flat Slabs	▪ *Minimise the number of angles around the perimeter*	*4.62 m^2/mh and 1.13 m^2/mh average losses in formwork labour productivity of fixing plywood and timber boards edges respectively as the ratio of the total number of angles around the perimeter to the total perimeter length increases by one unit*		*Eqs. 6.5 and 6.6*
		15% average loss in rebar fixing labour productivity is associated with fixing reinforcement in non-rectangular compared to rectangular slabs		*Eqs. 7.4 and 7.5*

[1]*Although the impact of this buildability factor is not statistically significant, applying the recommendation stated in the table would further improve the labour productivity of the activity.*

Table 10.1 Design Guidelines for Buildability and Productivity Improvements (cont'd)

Activity	***Recommendation(s)***	***Impact on Macro-Level Labour Productivity***	***Impact on Micro-Level Labour Productivity***	***Reference(s)***
Base and Suspended Flat Slabs (cont'd)	▪ *Specify large rebar diameter*	*7.43 kg/mh average gain in rebar fixing labour productivity as the rebar diameter increases by one millimeter*	*8.71 kg/mh average gain in rebar fixing labour productivity as the rebar diameter increases by one millimetre*	*Eqs. 7.4 and 7.6*
Columns and Walls	▪ *Minimise Circular Columns*	*0.012 m²/mh average loss in formwork labour productivity as the percentage of circular columns in the activity increases by one percent*	*29% average loss in formwork labour productivity is associated with shuttering circular compared to rectangular columns*	*Eqs. 6.11, 6.13 and 6.14*
		0.29 kg/mh average loss in rebar fixing labour productivity as the percentage of reinforcement fixed in circular columns increases by one percent.	*38% average loss in rebar fixing labour productivity is associated with fixing reinforcement in circular compared to rectangular columns*	*Eqs. 7.9, 7.10 and 7.12*
	▪ *Where possible, combine several collinear columns and/or walls in close proximity to one another into a single large column or wall*	*0.16 m²/mh and 0.0013 m²/mh average gains in formwork labour productivity as the average and total shutter areas of columns and walls increase by one square metre respectively*	*0.38 m²/mh average gain in formwork labour productivity as the shutter area of an individual column increases by one square metre*	*Eqs. 6.11, 6.13 and 6.15*
		0.00064 kg/mh and 0.0037 kg/mh average gains in rebar fixing labour productivity as the total quantity of reinforcement fixed in columns and walls increase by one kilogram respectively	*0.11 kg/mh average gain in fixing labour productivity as the quantity of reinforcement fixed in an individual column increases by one kilogram*	*Eqs. 7.9, 7.10 and 7.13*

Table 10.1 Design Guidelines for Buildability and Productivity Improvements (cont'd)

Activity	Recommendation(s)	Impact on Macro-Level Labour Productivity	Impact on Micro-Level Labour Productivity	Reference(s)
Columns and Walls (cont'd)	▪ *Repeat column dimensions from floor to floor and vary the quantity of reinforcement as applicable*	*7% average gain in formwork labour productivity compared to first formed columns is achieved as a result of repetition*		*Eqs. 6.11 and 6.12*
	▪ *Minimise the variability of column sizes*	[1]*0.0036 m²/mh average loss in formwork labour productivity as the total number of different column sizes increases by one unit*		*Eq. 6.11*
		0.64 kg/mh average loss in rebar fixing labour productivity as the total number of different column sizes increases by one unit		*Eq. 7.9*
	▪ *Minimise the number of angles on wall perimeter*	*0.25 m²/mh average loss in formwork labour productivity as the ratio of the number of angles on the perimeter to the perimeter length increases by one unit*		*Eq. 6.15*
	▪ *Specify large rebar diameter*	*6.76 kg/mh and 2.02 kg/mh average gains in fixing labour productivity as the rebar diameter increases by one millimetre in columns and walls respectively*	*4.98 kg/mh average gain in rebar fixing labour productivity as the rebar diameter increases by one millimetre in columns*	*Eqs. 7.9, 7.10 and 7.13*
	▪ *Provide adequate wall thickness for rebar fixing*	*0.41 kg/mh average gain in rebar fixing labour productivity as the wall thickness increases by one millimetre*		*Eq. 7.13*

[1]*Although the impact of this buildability factor is not statistically significant, applying the recommendation stated in the table would further improve the labour productivity of the activity.*

Table 10.1 Design Guidelines for Buildability and Productivity Improvements (cont'd)

Activity	***Recommendation(s)***	***Impact on Macro-Level Labour Productivity***	***Impact on Micro-Level Labour Productivity***	***Reference(s)***
Suspended Floors	▪ *Where applicable, use flat plates, otherwise, minimise the number and dimensions, i.e. width and depth, of beams in the floor framing system*	*1.72 m^2/mh average loss in formwork labour productivity as the ratio of the total shutter area of beams in the floor to the area of floor supported by those beams increases by one unit*		*Eq. 6.16*
		0.0042 m^2/mh average gain in formwork labour productivity as the average slab area in the floor increases by one square metre	*0.088 m^2/mh average gain in formwork labour productivity as the slab panel area increases by one square metre*	*Eqs. 6.16 and 6.25*
		0.059 kg/mh average gain in rebar fixing labour productivity as the average slab area in the floor increases by one square metre		*Eq. 7.20*
		0.036 kg/mh and 0.050 kg/mh average losses in rebar fixing labour productivity as the average width and depth of beams in the floor increases by one millimetre respectively	*0.052 kg/mh and 0.0083 kg/mh average losses in rebar fixing labour productivity as the width and depth of beams in the floor increases by one millimetre respectively*	*Eqs. 7.14 and 7.17*

Table 10.1 Design Guidelines for Buildability and Productivity Improvements (cont'd)

Activity	***Recommendation(s)***	***Impact on Macro-Level Labour Productivity***	***Impact on Micro-Level Labour Productivity***	***Reference(s)***
Suspended Floors (cont'd)	▪ *Where applicable, repeat the architectural and structural floor layout in multi-storey buildings*	*21% average gain in formwork labour productivity compared to first formed floors is achieved as a result of repetition*	*8% and 29% average gains in formwork labour productivity of forming individual rectangular and non-rectangular slab panels respectively are achieved as a result of repetition*	*Eqs. 6.16, 6.17, 6.25, 6.26 and 6.27*
			21% and 63% average gains in formwork labour productivity of forming individual linear, i.e. straight, and curved beams respectively are achieved as a result of repetition	*Eqs. 6.19, 6.20 and 6.21*
	▪ *Minimise beam intersections in the floor framing system*	*0.012 m^2/mh average loss in formwork labour productivity as the total number of beam intersections in the floor increases by one unit*	*0.31 m^2/mh average loss in formwork labour productivity as the number of beam intersections increases by one unit*	*Eqs. 6.16 and 6.19*

Table 10.1 Design Guidelines for Buildability and Productivity Improvements (cont'd)

Activity	***Recommendation(s)***	***Impact on Macro-Level Labour Productivity***	***Impact on Micro-Level Labour Productivity***	***Reference(s)***
Suspended Floors (cont'd)	▪ *Minimise the variability of beam sizes in the floor*	*[1]0.016 m^2/mh average loss in formwork labour productivity as the total number of different beam sizes in the floor increases by one unit*		*Eq. 6.16*
		0.34 kg/mh average loss in rebar fixing labour productivity as the total number of different beam sizes in the floor increases by one unit		*Eq. 7.14*
	▪ *Minimise non-rectangular slab panels in the floor*	*0.0070 m^2/mh average loss in formwork labour productivity as the percentage of non-rectangular slab panels in the floor increases by one percent*	*35% and 23% average losses in formwork labour productivity are associated with first and repeated formed individual non-rectangular compared to rectangular slab panels respectively*	*Eqs. 6.16, 6.25, 6.28 and 6.29*
		0.48 kg/mh average loss in rebar fixing labour productivity as the percentage of reinforcement fixed in non-rectangular slab panels increases by one percent	*38% average loss in rebar fixing labour productivity is associated with fixing reinforcement in an individual non-rectangular compared to rectangular slab panel*	*Eqs. 7.20, 7.22 and 7.23*

[1]Although the impact of this buildability factor is not statistically significant, applying the recommendation stated in the table would further improve the labour productivity of the activity.

Table 10.1 Design Guidelines for Buildability and Productivity Improvements (cont'd)

Activity	*Recommendation(s)*	*Impact on Macro-Level Labour Productivity*	*Impact on Micro-Level Labour Productivity*	*Reference(s)*
Suspended Floors (cont'd)	▪ *Minimise curved beams in the floor*	*0.021 m²/mh average loss in formwork labour productivity as the percentage of curved beams in the floor increases by one percent*	*88% and 84% average losses in formwork labour productivity are associated with first and repeated formed individual curved compared to linear beam respectively*	*Eqs. 6.16, 6.19, 6.22 and 6.23*
		0.39 kg/mh average loss in rebar fixing labour productivity as the percentage of reinforcement fixed in curved beams increases by one percent	*38% average loss in rebar fixing labour productivity is associated with fixing reinforcement in an individual curved compared to linear beam*	*Eqs. 7.14, 7.17, 7.18 and 7.19*
	▪ *Specify large rebar diameter for longitudinal reinforcement in beams and slabs and small rebar diameter for stirrups in beams*	*6.70 kg/mh and 11.79 kg/mh average gains in rebar fixing labour productivity as the rebar diameter increases by one millimetre in beams and slabs respectively*	*6.23 kg/mh and 15.97 kg/mh average gains in rebar fixing labour productivity as the rebar diameter fixed in individual beams and slabs increases by one millimetre respectively*	*Eqs. 7.14, 7.17, 7.20 and 7.22*
		10% average loss in rebar fixing labour productivity is associated with fixing 10 mm compared to 8 mm in diameter stirrups in beams.		*Eqs. 7.14 and 7.15*

Table 10.1 Design Guidelines for Buildability and Productivity Improvements (cont'd)

Trade	*Recommendation(s)*	*Impact on Pumped Concrete Labour Productivity*	*Impact on Skipped Concrete Labour Productivity*	*Reference(s)*
Concreting	▪ *Specify high workability concrete*	*In comparison with high workability mix, 23% average loss in pumped concrete labour productivity is associated with pouring medium workability concrete*	*In comparison with high workability mix, 30% average loss in skipped concrete labour productivity is associated with pouring medium workability concrete*	*Eqs. 8.1, 8.2, 8.5 and 8.6*
		In comparison with low workability mix, 59% average gain in pumped concrete labour productivity is associated with pouring medium workability concrete	*In comparison with low workability mix, 58% average gain in skipped concrete labour productivity is associated with pouring medium workability concrete*	*Eqs. 8.1, 8.3, 8.5 and 8.7*
		In comparison with low workability mix, 108% average gain in pumped concrete labour productivity is associated with pouring high workability concrete	*In comparison with low workability mix, 125% average gain in skipped concrete labour productivity is associated with pouring high workability concrete*	*Eqs. 8.1, 8.4, 8.5 and 8.8*
	▪ *Avoid rebar congestion in members*	*0.0018 m^3/mh average loss in pumped concrete labour productivity as the steel congestion ratio increases by one kg/m^3*	*0.00096 m^3/mh average loss in skipped concrete labour productivity as the steel congestion ratio increases by one kg/m^3*	*Eqs. 8.1 and 8.5*

Table 10.2 Site Management Control for Productivity Improvement

Trade	*Recommendation(s)*	*Impact on Pumped Concrete Labour Productivity*	*Impact on Skipped Concrete Labour Productivity*	*Reference(s)*
Concreting	▪ *Avoid small volume pours*	*0.0032 m^3/mh average gain in pumped concrete labour productivity as the volume of concrete increases by one cubic metre*	*0.0062 m^3/mh average gain in skipped concrete labour productivity as the volume of concrete increases by one cubic metre*	*Eqs. 8.1 and 8.5*
	▪ *Balance resources to compensate for labour productivity loss due to height increase above ground level*	*0.024 m^3/mh average loss in pumped concrete labour productivity as the height above ground level increases by one metre*	*0.0083 m^3/mh average loss in pumped concrete labour productivity as the height above ground level increases by one metre*	*Eqs. 8.1 and 8.5*

The guidelines and recommendations presented were based upon specific buildability knowledge deduced from the outcome of this project, and further classified into layout, dimensioning, detailing and exogenous knowledge. The layout and dimensioning knowledge is used to give architects and structural designers feedback on how well the designed building considers the requirements of buildability and the consequences on site labour productivity. Detailing knowledge directs designers to future design steps and also quantifies the effects of their decisions on the efficiency of the construction process. Exogenous knowledge points to further investigations required to determine the applicability and adequacy of a certain construction method or site management decision in the overall project context.

Chapter Eleven

Conclusions and Recommendations for Further Research

11.1 Major Conclusions

There is widespread consensus that design is becoming increasingly important in determining competitiveness. In today's economic climate, the construction industry is suffering from increasing costs stemming from poor buildability and reduced productivity. Buildable design facilitates ease of construction, enhances site efficiency and minimises building cost. On the other hand, designers applying the basic buildability principles will also optimise their workload through increasing the demand for their services.

Due to the importance of *in situ* reinforced concrete material to the construction industry, this research focused on exploring and quantifying the influence of buildability factors on the labour productivity of its major trades, namely, formwork, reinforcing steel, concrete placing and finishing. Since this type of construction is labour intensive, improving the labour productivity would reduce the risk of labour costs overrun and increases the efficiency of the operations.

The investigation proceeded at both levels, macro and micro, and covered the main building elements such as, foundations, ground beams and slabs, columns, walls, suspended beams and slab panels. Due to its potential impact on labour productivity, the applicability of the learning curve theory to formwork, reinforcing steel and pumped concrete was also investigated using the unit straight-line learning curve model.

Several findings and conclusions pertaining to the explored trades have been drawn from this study. However, it is important to note that such findings are to be interpreted when all the relevant buildability factors are included in the corresponding regression model. In addition, when quantifying the unique influence of a particular factor on labour productivity, it is implicitly assumed that all other relevant factors in the model are held constant.

11.1.1 Formwork

1. Grid pattern of isolated foundations and columns has a significant influence on the labour productivity of axes setting-out activity. Symmetrical and uniform grid layout is associated with higher labour productivity than irregular and scattered layout. As the ratio of the total number of elements, i.e. isolated foundations and columns, to the total number of axes increases by one unit, the labour productivity significantly increases, on average, by 1.56 and 1.97 footings/mh and columns/mh for isolated foundations and columns respectively.

2. A consistent positive relationship between area of forms erected and labour productivity is realised in all observed activities and elements. The average rate of labour productivity increase for every square meter increase is however different for different activities and observation level, i.e. macro and micro.

3. The presence of circular columns has a negative impact on macro-level shuttering labour productivity. On average, as the percentage of circular columns in floors increases by one percent, labour productivity significantly decreases by 0.0124 m^2/mh. Moreover, in comparison with shuttering rectangular columns, an average significant loss of 29% in micro-level labour productivity is associated with circular columns formwork.

4. Notwithstanding that the variability of element sizes has a negative effect on labour productivity, its influence is not statistically significant. This finding is consistent amongst all related observed activities, i.e. isolated foundations, ground beams, columns and suspended beams.

5. The perimeter geometry of raft foundations, ground slabs, floor edges and walls has a significant impact on formwork labour productivity. As the ratio of the total number of angles around the perimeter to the total length of the perimeter increases by one unit, labour productivity decreases, on average, by 4.62, 1.13 and 0.250 m^2/mh for raft foundations, slab edges and walls respectively.

6. The presence of dropped beams in structural framing plans has a significant adverse influence on macro-level labour productivity of floor formwork activities. As the ratio of the total form area of beams to the area of the floor supported by those beams increases by one unit, the average labour productivity significantly decreases by 1.72 m^2/mh.

7. The span geometry of beams has a significant impact on formwork labour productivity. At the macro-level investigation, for a unit increase in the percentage of curved beams in floors, an average loss of 0.0209 m^2/mh in labour productivity is determined. In addition, the average difference between micro-level labour productivity of curved and linear beams is quantified for both form repetition categories; repeated and first formed beams. On average, significant losses of 88% and 84% in labour productivity, in comparison with linear beams, are associated with first and repeated formed curved beams respectively.

8. Structural plans in which beams are designed to support other beams in a floor result in a significant loss in formwork labour productivity of the supporting beams. The average labour productivity losses of 0.0203 and 0.0987 m^2/mh for a unit increase in the number of beam intersections are determined for macro and micro-level formwork labour productivity of ground beams respectively. In addition, suspended floor beams, are associated with average macro and micro-level labour productivity losses of 0.0117 and 0.305 m^2/mh respectively for each unit increase in the number of such intersections.

9. Panel geometry of suspended slabs has a significant effect on formwork labour productivity. In comparison with rectangular slab panels, non-rectangular panels are associated with a significant loss in labour productivity. At the macro-level, increasing the percentage of non-rectangular floor panels in floors by one unit, labour productivity, on average, decreases by 0.00700 m^2/mh. Moreover, the average losses of 35% and 23% in micro-level labour productivity for both repetition categories, i.e. first and repeated formed panels, relative to rectangular slab panels, are associated with forming non-rectangular slab panels respectively.

10. The repetition effect of floors, columns, beams and slab panels has a significant positive influence on formwork labour productivity. Building floors and columns observed at the macro-level are accompanied by 21% and 7% average gains in labour productivity due to the saving achieved in measurements and cutting as a result of material repetition respectively. Furthermore, the significant impact of forms repetition is revealed in beam activities. Whilst an average gain of 21% in micro-level labour productivity is achieved in linear beams, on average, 63% increase in labour productivity is realised in forming curved beams. This pattern is also consistent in slab panels. An average gain of 8% is achieved in micro-level labour productivity of rectangular panels whereas, 29% increase in labour productivity is realised in forming non-rectangular slab panels. The quantified results, in particular those associated with forming complex shapes, such as curved beams and non-rectangular slab panels, clearly indicate the importance of material repetition to formwork labour productivity.

11. For all investigated activities, the ranks and relative influence of significant buildability factors on formwork labour productivity at both observed levels, macro and micro, are summarised as follows:

Table 11.1 Ranks and Relative Influence of Buildability Factors on Macro-Level Formwork Labour Productivity of Isolated Foundations

Factor	***Influence Rank***	***Relative Influence***
Average Shutter Area (m^2)	1	*1.00*
Total Shutter Area (m^2)	2	*0.84*
Axes Layout	3	*0.46*

Table 11.2 Ranks and Relative Influence of Buildability Factors on Formwork Labour Productivity of Raft Foundations

Factor	***Influence Rank***	***Relative Influence***
Geometric Factor	*1*	*1.00*
Total Shutter Area (m^2)	*2*	*0.78*

Table 11.3 Ranks and Relative Influence of Buildability Factors on Formwork Labour Productivity of Ground Slabs and Floor Edges

Factor	*Influence Rank*	*Relative Influence*
Geometric Factor	1	1.00
Total Shutter Area (m^2)	2	0.66

Table 11.4-a Ranks and Relative Influence of Buildability Factors on Macro-Level Formwork Labour Productivity of Ground Beams

Factor	*Influence Rank*	*Relative Influence*
Total Shutter Area (m^2)	1	1.00
Total Number of Joints	2	0.26

Table 11.4-b Ranks and Relative Influence of Buildability Factors on Micro-Level Formwork Labour Productivity of Ground Beams

Factor	*Influence Rank*	*Relative Influence*
Shutter Area (m^2)	1	1.00
Number of Joints in Beam	2	0.11

Table 11.5 Ranks and Relative Influence of Buildability Factors on Macro-Level Formwork Labour Productivity of Columns

Factor	*Influence Rank*	*Relative Influence*
Percentage of Circular Columns	1	1.00
Average of Shutter Area (m^2)	2	0.83
Axes Layout	3	0.60
Total Shutter Area (m^2)	4	0.44

Table 11.6 Ranks and Relative Influence of Buildability Factors on Formwork Labour Productivity of Walls

Factor	*Influence Rank*	*Relative Influence*
Total Shutter Area (m^2)	1	1.00
Geometric Factor	2	0.14

Table 11.7 Ranks and Relative Influence of Buildability Factors on Macro-Level Formwork Labour Productivity of Suspended Floors

Factor	Influence Rank	Relative Influence
Average Panel Area (m^2)	*1*	*1.00*
Beam-Floor Ratio	*2*	*0.85*
Floor Area (m^2)	*3*	*0.57*
Total Number of Joints in Beams	*4*	*0.41*
Percentage of Non-rectangular Panels	*5*	*0.25*
Percentage of Curved Beams	*6*	*0.23*

Table 11.8 Ranks and Relative Influence of Buildability Factors on Micro-Level Formwork Labour Productivity of Suspended Beams

Factor	Influence Rank	Relative Influence
Shutter Area (m^2)	*1*	*1.00*
Number of Joints in Beam	*2*	*0.28*

11.1.2 Reinforcing Steel

1. A significant positive relationship between steel fixing labour productivity and bar diameter was determined. The average rate of labour productivity improvement for every one-millimetre increase in bar diameter is different for different activities and observation level, i.e. macro and micro.

2. The quantity of reinforcement has a significant positive influence on steel fixing labour productivity. As the quantity of reinforcement fixed increases, labour productivity increases. The average rate of labour productivity improvement for every one-kilogram increase in the quantity of reinforcement is different for different activities and observation level.

3. Although the negative effect of variability of element sizes on reinforcing steel fixing labour productivity is not statistically significant in isolated foundations activity, a significant negative influence of this variable is observed in columns and beams. As the total number of different

element sizes increases by one unit, average losses of 0.638 and 0.341 kg/mh are realised in labour productivity of columns and beams respectively.

4. Slab geometry has a significant impact on fixing labour productivity. On average, a significant loss of 15% in macro-level labour productivity is associated with fixing reinforcement in non-rectangular relative to rectangular base and suspended flat slabs. In addition, as the percentage of reinforcement quantity fixed in non-rectangular slab panels increases by one unit in the observed floors, an average loss of 0.484 kg/mh in macro-level labour productivity is realised. Furthermore, compared to rectangular panels, individual non-rectangular slab panels observed at the micro-level are associated with an average reduction of 38% in fixing labour productivity.

5. Layer location of reinforcing steel bars in base and suspended flat slabs has a significant impact on fixing labour productivity. Whilst an average loss between fixing top and bottom steel of 15% is quantified in rectangular, an average loss of 13% is determined in non-rectangular shapes.

6. Whilst fixing reinforcement in top layers is associated with lower labour productivity than bottom layers in base and suspended flat slabs, an opposite pattern exists in individual slab panels having, on average, larger quantity of reinforcement and bar diameter. It is therefore reasonable to conclude that the influence of reinforcement quantity and bar diameter on labour productivity is stronger than the layer location.

7. Column geometry has a significant influence on steel fixing labour productivity. The presence of circular columns has a negative impact on macro-level labour productivity. On average, as the percentage of reinforcement quantity fixed in circular columns increases by one unit, labour productivity decreases by 0.289 kg/mh. Moreover, In comparison with rectangular columns, an average loss of 38% in micro-level labour productivity is associated with fixing reinforcement in circular columns.

8. A significant positive relationship between wall thickness and steel fixing labour productivity was determined. As the thickness of wall increases by one millimetre, the labour productivity increases, on average, by 0.411 kg/mh.

9. The effect of stirrups' bar diameter has a significant influence on reinforcing steel fixing labour productivity of beams. The macro-level labour productivity of fixing 10 mm stirrups is, on average, 10% lower than fixing 8 mm stirrups.

10. At both observation levels, macro and micro, as the width and depth of beams increase, reinforcing steel fixing labour productivity significantly decreases. Beams observed at the macro-level are associated with average losses of 0.0500 and 0.0363 kg/mh in labour productivity for a one-millimetre increase in beam depth and width respectively. This pattern is also consistent in beams observed at the micro-level. Whilst an average loss of 0.00832 kg/mh in labour productivity is quantified for every one-millimetre increase in beam depth, on average, a loss of 0.0515 kg/mh is associated with increasing the beam width by one millimetre.

11. Span geometry of beams has a significant impact on reinforcing steel fixing labour productivity. Macro-level observation of beams revealed an average loss of 0.391 kg/mh as the percentage of curved reinforcement in floor beams increases by one unit. Moreover, curved beams observed at the micro-level are associated with an average loss of 38% in labour productivity compared to linear beams.

12. The ranks and relative influence of significant buildability factors on reinforcing steel fixing labour productivity at both observed levels, macro and micro, are summarised as follows:

Table 11.9-a Ranks and Relative Influence of Buildability Factors on Macro-Level Reinforcing Steel Labour Productivity of Isolated Foundations

Factor	***Influence Rank***	***Relative Influence***
Characteristic Bar Diameter (mm)	*1*	*1.00*
Total Quantity Fixed (kg)	*2*	*0.44*

Table 11.9-b Ranks and Relative Influence of Buildability Factors on Micro-Level Reinforcing Steel Labour Productivity of Isolated Foundations

Factor	*Influence Rank*	*Relative Influence*
Characteristic Bar Diameter (mm)	*1*	*1.00*
Quantity Fixed (kg)	*2*	*0.41*

Table 11.10 Ranks and Relative Influence of Buildability Factors on Macro-Level Reinforcing Steel Labour Productivity of Base and Suspended Flat Slabs

Factor	*Influence Rank*	*Relative Influence*
Characteristic Bar Diameter (mm)	*1*	*1.00*
Total Quantity Fixed (kg)	*2*	*0.37*

Table 11.11 Ranks and Relative Influence of Buildability Factors on Micro-Level Reinforcing Steel Labour Productivity of Base and Suspended Flat Slabs

Factor	*Influence Rank*	*Relative Influence*
Characteristic Bar Diameter (mm)	*1*	*1.00*
Quantity Fixed (kg)	*2*	*0.33*

Table 11.12-a Ranks and Relative Influence of Buildability Factors on Macro-Level Reinforcing Steel Labour Productivity of Columns

Factor	*Influence Rank*	*Relative Influence*
Characteristic Bar Diameter (mm)	*1*	*1.00*
Percentage of Steel Fixed in Circular Columns	*2*	*0.34*
Total Quantity Fixed (kg)	*3*	*0.11*
Variability of Column Sizes	*4*	*0.10*

Table 11.12-b Ranks and Relative Influence of Buildability Factors on Micro-Level Reinforcing Steel Labour Productivity of Columns

Factor	*Influence Rank*	*Relative Influence*
Characteristic Bar Diameter (mm)	*1*	*1.00*
Quantity Fixed (kg)	*2*	*0.78*

Table 11.13 Ranks and Relative Influence of Buildability Factors on Reinforcing Steel Labour Productivity of Walls

Factor	Influence Rank	Relative Influence
Total Quantity Fixed (kg)	*1*	*1.00*
Wall Thickness (mm)	*2*	*0.51*
Characteristic Bar Diameter (mm)	*3*	*0.26*

Table 11.14-a Ranks and Relative Influence of Buildability Factors on Macro-Level Reinforcing Steel Labour Productivity of Beams

Factor	Influence Rank	Relative Influence
Characteristic Bar Diameter (mm)	*1*	*1.00*
Total Quantity Fixed (kg)	*2*	*0.79*
Average Depth of Beam (mm)	*3*	*0.31*
Variability of Beam Sizes	*4*	*0.26*
Percentage of Steel Fixed in Curved Beams	*5*	*0.18*
Average Width of Beam (mm)	*6*	*0.16*

Table 11.14-b Ranks and Relative Influence of Buildability Factors on Micro-Level Reinforcing Steel Labour Productivity of Beams

Factor	Influence Rank	Relative Influence
Characteristic Bar Diameter (mm)	*1*	*1.00*
Quantity Fixed (kg)	*2*	*0.70*
Width of Beam (mm)	*3*	*0.31*
Depth of Beam (mm)	*4*	*0.0841*

Table 11.15-a Ranks and Relative Influence of Buildability Factors on Macro-Level Reinforcing Steel Labour Productivity of Slab Panels

Factor	Influence Rank	Relative Influence
Characteristic Bar Diameter (mm)	*1*	*1.00*
Percentage of Steel in Non-rectangular Panels	*2*	*0.73*
Total Quantity Fixed (kg)	*3*	*0.29*
Average Area of Panels (m^2)	*4*	*0.16*

Table 11.15-b Ranks and Relative Influence of Buildability Factors on Micro-Level Reinforcing Steel Labour Productivity of Slab Panels for the Total Quantity of Reinforcement Fixed

Factor	*Influence Rank*	*Relative Influence*
Characteristic Bar Diameter (mm)	*1*	*1.00*
Quantity Fixed (kg)	*2*	*0.99*

11.1.3 Concreting and Trowelling

1. The volume of placed concrete, height above ground level, steel congestion ratio and the workability of the mix are the major factors influencing pumped and skipped concrete labour productivity.

2. There is a significant relationship between volume of concrete placed and labour productivity for both placement methods, pumped and skipped, and the pattern is consistent. As the volume increases by one cubic meter, labour productivity increases, on average, by 0.00322 and 0.00618 m^3/mh for pumped and skipped concrete respectively.

3. For pumped and skipped placement methods, height above ground level has a significant impact on labour productivity. As the height increases by one metre above ground, labour productivity decreases, on average, by 0.0238 and 0.00834 m^3/mh for pumped and skipped concrete respectively.

4. For both placement methods, as the steel congestion ratio increases by one unit, concreting labour productivity significantly decreases, on average, by 0.00181 and 0.000956 m^3/mh for pumped and skipped concrete respectively.

5. Concrete workability has a significant effect on pumped and skipped concrete labour productivity. For both placement methods, as the workability of concrete mix decreases, the labour productivity decreases. On average, pumping medium workability concrete is associated with 23% loss in labour productivity in comparison with the high workability mix. An average gain in labour productivity of 59% is observed in pumping medium workability concrete relative to the low

workability category, whereas an average gain of 108% in labour productivity is associated with pumping high workability mix in comparison with low workability concrete.

The same pattern is also realised in skipped concrete. An average loss of 30% in labour productivity is realised with medium workability mix in comparison with high workability. An average gain of 58% in labour productivity is achieved as a result of placing medium relative to low workability skipped concrete, and an average gain of 125% in labour productivity is associated with high compared to low workability mix.

6. A summary of the rank and relative influence of significant buildability factors on pumped and skipped concrete labour productivity is provided as follows:

Table 11.16-a Ranks and Relative Influence of Buildability Factors on Pumped Concrete Labour Productivity

Factor	***Influence Rank***	***Relative Influence***
Volume (m^3)	*1*	*1.00*
Height above Ground Level (m)	*2*	*0.35*
Steel Congestion Ratio (kg/m^3)	*3*	*0.18*

Table 11.16-b Ranks and Relative Influence of Buildability Factors on Skipped Concrete Labour Productivity

Factor	***Influence Rank***	***Relative Influence***
Volume (m^3)	*1*	*1.00*
Steel Congestion Ratio (kg/m^3)	*2*	*0.46*
Height above Ground Level (m)	*3*	*0.45*

7. Whilst a positive relationship between the floor area and trowelling productivity was identified, there is a negative relationship between the number of machines used and trowelling productivity. On average, as the floor area increases by one square metre, trowelling productivity increases by 0.0469 m^2/mh, whereas, for every additional trowelling machine used, an average loss of 9.13 m^2/mh in trowelling productivity is realised.

8. A summary of the ranks and relative influence of the investigated factors on trowelling productivity is shown below:

Table 11.17 Ranks and Relative Influence of Floor Area and Number of Machines on Trowelling Productivity

Factor	*Influence Rank*	*Relative Influence*
Area of Floor (m^2)	*1*	*1.00*
Number of Trowelling Machines	*2*	*0.69*

11.1.4 The Applicability of Learning Curve Theory to *in situ* Reinforced Concrete Construction

The unit straight-line learning curve model was used to quantify the effect of learning phenomenon on formwork, reinforcing steel fixing and pumped concrete labour productivity. A total of twenty-one different multi-storey buildings having identical floors ranging from a minimum of four to a maximum of ten, with an overall average floor number of six for formwork and seven for reinforcing steel and pumped concrete, were selected for this investigation. Labour inputs of formwork, fixing reinforcement in beams and slabs, and concreting recurring floors were monitored against the cycle, i.e. floor, number.

As we have previously illustrated in chapter three, in order to minimise the influence of material repetition on formwork labour productivity and unravel the effect of repetition due to learning, the labour input of cycles in which formwork was erected for the first time was discarded from the analysis.

None of the twenty-one monitored buildings exhibited a significant improvement in labour productivity due to repetition of floor formwork activities. On the contrary, 71% of the monitored buildings showed an increase in labour inputs rather than the expected decrease as the cycle number increased.

The outcome of investigating the influence of learning on reinforcing steel fixing labour productivity in beams and slabs revealed an inconsistent sporadic pattern. Although a significant influence of learning was exhibited in some buildings, other buildings showed either an insignificant reduction or an increase in labour inputs as the cycle number increased. Based on the developed learning curves, only 31% and 19% of the monitored buildings exhibited a significant reduction in reinforcing steel fixing labour inputs for beams and slabs respectively.

The effect of learning on pumped concrete labour productivity could not be determined in this study. In all monitored buildings, a consistent positive relationship between concreting labour inputs and the cycle number was quantified. Consequently, we may conclude that even if learning has a significant influence on pumped concrete labour productivity, its effect has been masked and overshadowed by a stronger negative impact of height.

In conclusion, the findings of this investigation indicate that the learning curve theory is of little importance to *in situ* reinforced concrete construction, and has no potential as a useful tool to quantify productivity improvement, allocate resources or schedule activity durations.

11.2 Summary of Research Contributions

1. This project has quantified the relationship between the principal design characteristics of *in situ* reinforced concrete construction and labour productivity of the various trades involved. If implemented, the design recommendations previously presented in chapter ten, can provide practical guidance to designers who seek to enhance the buildability of their designs. It can also give a feedback on how well the designed building considers the requirements of the basic buildability principles and provides for tangible consequences of their decisions on construction labour productivity. In addition, management control guidelines were recommended for specific buildability knowledge, which is beyond the control of the designer, but can be controlled by the site management.

2. The study showed that the effect of the learning curve theory on reinforced concrete trades, i.e. formwork, reinforcing steel and pumped concrete, is of little importance and may provide unreliable estimates of productivity improvement, resource planning or activity durations.

3. The quantified effects of buildability factors on labour productivity of the various investigated trades can be employed to quantify the implications of such factors on the required size of gang members and labour costs.

4. The findings of this research can be used to develop an automated formal "Buildability Design Support System". Such a system would be useful for formalising the specific buildability knowledge and guidelines to make them readily available to designers and constructors to improve project performance in an ever-increasing demand for faster and lower cost delivery of finished buildings.

In addition, the findings of this research have wider implications within the industry. Although this study focused on *in situ* reinforced concrete construction, the application of the basic buildability principles, i.e. design rationalisation, standardisation and repetition, on projects using other types of construction materials such as, pre-cast concrete, masonry, structural steel and timber might also have a significant positive influence on the labour productivity of the construction process. Furthermore, the significant impact of buildability on labour productivity quantified in this study can be employed as a useful tool in the design of fast-track construction, efficient utilisation of concrete pumps, tower and mobile cranes, and to minimise the queue time of truck mixers waiting to be unloaded on sites.

11.3 Recommendations for Further Research

In this research project, several aspects of buildability factors were investigated in terms of their influence upon the labour productivity of major reinforced concrete trades, activities and elements. However, the study exposed several factors which need to be further investigated so that their impacts on labour productivity could be verified and ascertained. In addition to following further recommended investigations, Improved buildability of design can be achieved through emphasising the importance of this subject in universities so that graduates can implement its principles in the design environment.

11.3.1 Formwork

1. In this study, buildability factors influencing isolated and raft foundations were investigated and quantified. Other types of shallow reinforced concrete foundations, such as strap and wall foundations, should be the subjects of future research.

2. The effect of column geometry, other than rectangular and circular, e.g. L-shaped, oval, octagonal or hexagonal, on labour productivity should be investigated and quantified.

3. Due to the limited number of curved walls encountered within the observed projects, the investigation was limited to linear or straight walls. It is recommended that the impact of curved walls on labour productivity be the subject of future study.

4. Heights of columns and walls encountered within the observed projects were essentially of negligible difference, i.e. heights were in the range from 3.20 m to 4.00 m. Therefore, the influence of height on labour productivity of such elements could not be determined. It is recommended therefore that the effect of this buildability factor be the subject of future investigation.

5. In this project, the influence of buildability factors on formwork labour productivity was limited to traditional timber material. It is recommended that this study be repeated for other types of formwork materials, e.g. metal and plastic.

11.3.2 Reinforcing Steel

1. In all observed projects, the maximum size of reinforcing steel bar diameter encountered was 25 mm. The influence of bar diameters larger than 25 mm on steel fixing labour productivity should be further explored.

2. In this research, the influence of buildability factors on reinforcing steel labour productivity was limited to *in situ* fixing, i.e. placing and tying reinforcement in positions. It is recommended that

the effects of bar diameter and quantity of reinforcement on cutting and bending, and the impact of fixing pre-fabricated reinforcement on labour productivity be the subjects of future research.

3. The effect of curved walls on steel fixing labour productivity should be the subject of future study.

4. The influence of column geometry, other than rectangular and circular, on fixing labour productivity should be also investigated and quantified.

5. The impact of height, i.e. greater than 4.00 meters, on steel fixing labour productivity of columns and walls should be the subject of future investigation.

6. In this study, the thickness of observed walls ranged from 150 mm to 300 mm, with an overall average of 210 mm. It is recommended that a wider range of wall thickness be investigated and its effect on fixing labour productivity be quantified.

7. An unexplainable shift in the relative influence of width and depth of beams on fixing labour productivity between macro and micro-level analysis requires further investigation in order to assert the relative influence of beam dimensions on labour productivity.

8. In this research project, the encountered stirrups in all observed beams were either 8 mm or 10 mm in diameter. It is recommended that the effect of other diameters, e.g. 6 mm and 12 mm, on fixing labour productivity be investigated and quantified.

9. Due to the limited number of 135-degree hooks of stirrups encountered on sites, the investigation was limited to fixing 90-degree hooks. Therefore, it is recommended that the impact of specifying 135-degree hooks for stirrups in beams on labour productivity be the subject of future study.

11.3.3 Concreting and Trowelling

1. Since pumped and skipped concrete were used in different members, i.e. horizontal versus vertical elements, and due to the effect of shape, a meaningful and valid comparison between the

labour productivity of the two placement methods was not possible. Therefore, it is recommended that this comparison be the subject of future research.

2. In this study, placement methods were limited to pumped and skipped concrete. Factors influencing concreting labour productivity of other placement methods, such as slip forming, shotcreteing and tremie concrete should be also investigated and quantified.

3. Due to the limited variations in heights of vertical members encountered in this study, i.e. columns and walls, the effect of height greater than 4.00 meters on skipped concrete labour productivity could not be determined. It is recommended therefore that the influence of this buildability factor on skipped concrete labour productivity be investigated and quantified.

4. Apart from surface levelling, power-trowelled concrete was the only other encountered finishing method on all sites observed. Therefore, the investigation of factors influencing concrete finishing productivity was limited to this type of surface finish. The effect of other finishing methods on labour productivity, e.g. screeding and texturing, should be the subject of future study.

5. In this research, a negative relationship between trowelling productivity and the number of machines used to conduct the activity was determined. This finding suggests that for a given floor area, there is an optimum number of machines which would lead to optimum trowelling productivity. It is recommended therefore that the question of the optimum number required for a given area to maximise the trowelling productivity be the subject of future investigation.

11.3.4 Learning Curve Theory

1. The outcome of this study contradicts much previous research in this area. In order to assert the findings of this research however, it is recommended that this investigation be replicated with a greater number of cycles, i.e. observation of several *in situ* reinforced concrete buildings having more than ten recurring floors.

2. It is also recommended that other learning curve models, e.g. Stanford "B" model, cubic power model, exponential or piecewise models, be used to investigate the influence of the learning phenomenon on *in situ* reinforced concrete trades.

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Appendix A

Productivity Data Collection Form
Site General Information

Date: Project No.: Form No.: A

1. **Site Management Level**

Position	No. of Personnel	Years of Experience
Project Manager		
Site Engineer		
Superintendent		
Foreman		

2. **Space Restriction:**

3. **Other Restrictions:**

(E.g. Power Cables Crossings, Restricted Access, etc.)

4. **Number of Normal Working Hours per Day:**

5. **Project Description**

Project Type	No. of Stories	Total Floor Area (m^2)	Frame Type	Contract Procurement Method

6. **Formwork**

Type	Storage	Gang/Crew Employment Method
	❒ On-Site ❒ Off-Site	❒ Direct ❒ Subcontract

7. **Reinforcing Steel**

Storage	Fabrication	Gang/Crew Employment Method
❒ On-Site ❒ Off-Site	❒ On-Site ❒ Off-Site	❒ Direct ❒ Subcontract

8. **Concreting**

Type of Delivery	Casting Method	Workability	Type of Finish	Gang/Crew Employment Method
	❒ Crane ❒ Pump ❒ Other	❒ High ❒ Medium ❒ Low	❒ Rough ❒ Leveled ❒ Trowelled	❒ Direct ❒ Subcontract

Remarks:

Appendix B

Site Process Information Sheet
Formwork

Date		Project No.		Form No.	F

Horizontal Elements

Please indicate all Elements that fall within this Category

Labour Source	❒Direct ❒Subcont.	Assembled	❒On-Site ❒Off-Site	Made	❒On-Site ❒Off-Site
Vertical Transport	❒Manual ❒Crane ❒Other		Horizontal Transport		❒Manual ❒Trailer ❒Crane ❒Other

Vertical Elements

Please indicate all Elements that fall within this Category

Labour Source	❒Direct ❒Subcont.	Assembled	❒On-Site ❒Off-Site	Made	❒On-Site ❒Off-Site
Vertical Transport	❒Manual ❒Crane ❒Other		Horizontal Transport		❒Manual ❒Trailer ❒Crane ❒Other

Other Elements

Please indicate all Elements that fall within this Category

Labour Source	❒Direct ❒Subcont.	Assembled	❒On-Site ❒Off-Site	Made	❒On-Site ❒Off-Site
Vertical Transport	❒Manual ❒Crane ❒Other		Horizontal Transport		❒Manual ❒Trailer ❒Crane ❒Other

Remarks:

Appendix C

Site Process Information Sheet
Reinforcing Steel

Date		Project No.		Form No.	S

Horizontal Elements

Please indicate all Elements that fall within this Category

Labour Source	❒Direct ❒Subcont.	Cut & Bent	❒On-Site ❒Off-Site	Prefabricated	❒On-Site ❒Off-Site ❒Fixed in-situ
Vertical Transport	❒Manual ❒Crane ❒Other	Horizontal Transport		❒Manual ❒Trailer ❒Crane ❒Other	

Vertical Elements

Please indicate all Elements that fall within this Category

Labour Source	❒Direct ❒Subcont.	Cut & Bent	❒On-Site ❒Off-Site	Prefabricated	❒On-Site ❒Off-Site ❒Fixed in-situ
Vertical Transport	❒Manual ❒Crane ❒Other	Horizontal Transport		❒Manual ❒Trailer ❒Crane ❒Other	

Other Elements

Please indicate all Elements that fall within this Category

Labour Source	❒Direct ❒Subcont.	Cut & Bent	❒On-Site ❒Off-Site	Prefabricated	❒On-Site ❒Off-Site ❒Fixed in-situ
Vertical Transport	❒Manual ❒Crane ❒Other	Horizontal Transport		❒Manual ❒Trailer ❒Crane ❒Other	

Remarks:

Appendix D

Site Process Information Sheet
Concreting

Date		Project No.		Form No.	C

Horizontal Elements

Please indicate all Elements that fall within this Category

Labour Source	❐ Direct ❐ Subcont.	Mixed	❐ On-Site ❐ Off-Site	Workability	❐ High ❐ Medium ❐ Low
Vertical Transport	❐ Pump ❐ Crane ❐ Other	Horizontal Transport	❐ Manual ❐ Pump ❐ Crane ❐ Other		

Vertical Elements

Please indicate all Elements that fall within this Category

Labour Source	❐ Direct ❐ Subcont.	Mixed	❐ On-Site ❐ Off-Site	Workability	❐ High ❐ Medium ❐ Low
Vertical Transport	❐ Pump ❐ Crane ❐ Other	Horizontal Transport	❐ Manual ❐ Pump ❐ Crane ❐ Other		

Other Elements

Please indicate all Elements that fall within this Category

Labour Source	❐ Direct ❐ Subcont.	Mixed	❐ On-Site ❐ Off-Site	Workability	❐ High ❐ Medium ❐ Low
Vertical Transport	❐ Pump ❐ Crane ❐ Other	Horizontal Transport	❐ Manual ❐ Pump ❐ Crane ❐ Other		

Remarks:

Appendix E

Macro-Level Productivity Data Collection Form Formwork

Date: Project No.: Form No: F-1

Element: Location:

Forms Assembly: ❐ 1st ❐ Repeated (To be checked only in Columns & Floors)

Total Input to Complete the Activity (man-hours):

Total Output (m^2):

No. of Normal Working Hours per Day:

Cause of Delays	* Total Delays (Man-Hrs)	Type of Delays
Weather		❐ Interruption ❐ Disruption
Waiting for Materials		❐ Interruption ❐ Disruption
Construction Rework		❐ Interruption ❐ Disruption
Design Rework		❐ Interruption ❐ Disruption
Waiting for Tools		❐ Interruption ❐ Disruption
Waiting for Inspection		❐ Interruption ❐ Disruption
Waiting for Information		❐ Interruption ❐ Disruption
Waiting for Plant		❐ Interruption ❐ Disruption
Unbalanced Crew		❐ Interruption ❐ Disruption
Crew Interference		❐ Interruption ❐ Disruption
Crowded Work Area		❐ Interruption ❐ Disruption
Moving to New Work Location		❐ Interruption ❐ Disruption
Fabrication Rework Material Supplied		❐ Interruption ❐ Disruption
Others (Specify) 1.		❐ Interruption ❐ Disruption
2.		❐ Interruption ❐ Disruption
Total (man-hours)		

*Only Duration of Delays lasting longer than 1/4th of an hour for Interrupted activities and longer than One-half the work-shift for Disrupted activities shall be recorded.

Remarks:

Appendix F

Macro-Level Productivity Data Collection Form
Reinforcing Steel

Date: Project No.: Form No: S-1

Element: Location: Total Output (Kg):

Characteristic Bar Dia. (mm): Characteristic Stirrups Dia. (mm):

Layer Location: ❐ Bottom ❐ Top (To be checked only in Base and Suspended Slabs)

Total Input to Complete the Activity (man-hours):

No. of Normal Working Hours per day:

Cause of Delays	* Total Delays (Man-Hrs.)	Type of Delays
Weather		❐ Interruption ❐ Disruption
Waiting for Materials		❐ Interruption ❐ Disruption
Construction Rework		❐ Interruption ❐ Disruption
Design Rework		❐ Interruption ❐ Disruption
Waiting for Tools		❐ Interruption ❐ Disruption
Waiting for Inspection		❐ Interruption ❐ Disruption
Waiting for Information		❐ Interruption ❐ Disruption
Waiting for Plant		❐ Interruption ❐ Disruption
Unbalanced Crew		❐ Interruption ❐ Disruption
Crew Interference		❐ Interruption ❐Disruption
Crowded Work Area		❐ Interruption ❐Disruption
Moving to New Work Location		❐ Interruption ❐ Disruption
Fabrication Rework Material Supplied		❐ Interruption ❐ Disruption
Others (Specify) 1.		❐ Interruption ❐ Disruption
2.		❐ Interruption ❐ Disruption
Total (man-hours)		

*Only Duration of Delays lasting longer than 1/4th of an hour for Interrupted activities and longer than One-half the work-shift for Disrupted activities shall be recorded.

Remarks:

Appendix G

Productivity Data Collection Form
Concreting

Date: Project No.: Form No: C-1

Element: Location: Volume Cast (m^3):

Height Above Ground Level (m): Total Area (m^2):

Total Input to Complete the Concreting Activity (man-hours):

Concrete Workability: ❐ High ❐ Medium ❐ Low

Casting Method: ❐ Pump No.:
❐ Crane No.:
❐ Other Specify:

Surface Finish: ❐ Rough ❐ Leveled ❐ Trowelled; Total No. of Machines used:

Other ❐ Specify:

Total Input to Complete the Trowelling Activity (man-hours):

Cause of Delays	* Total Delays (Man-Hrs)	Type of Delays
Weather		❐ Interruption ❐ Disruption
Waiting for Materials		❐ Interruption ❐ Disruption
Construction Rework		❐ Interruption ❐ Disruption
Design Rework		❐ Interruption ❐ Disruption
Waiting for Tools		❐ Interruption ❐ Disruption
Waiting for Inspection		❐ Interruption ❐ Disruption
Waiting for Information		❐ Interruption ❐ Disruption
Waiting for Plant		❐ Interruption ❐ Disruption
Unbalanced Crew		❐ Interruption ❐ Disruption
Crew Interference		❐ Interruption ❐ Disruption
Crowded Work Area		❐ Interruption ❐ Disruption
Moving to New Work Location		❐ Interruption ❐ Disruption
Fabrication Rework Material Supplied		❐ Interruption ❐ Disruption
Others (Specify) 1.		❐ Interruption ❐ Disruption
2.		❐ Interruption ❐ Disruption
Total (man-hours)		

* Only Durations of Delays lasting longer than 1/4th of an hour for Interrupted activities and longer than One-half the work-shift for Disrupted activities shall be recorded.

Remarks:

Appendix H

Micro-Level Productivity Data Collection Form
Formwork

Date:	Project No.:	Form No.: F-1'
Element observed:		Element Mark:
Starting Time:	Finishing Time:	Delays:
Total No. of Carpenters Worked to Complete the Activity:		

Appendix I

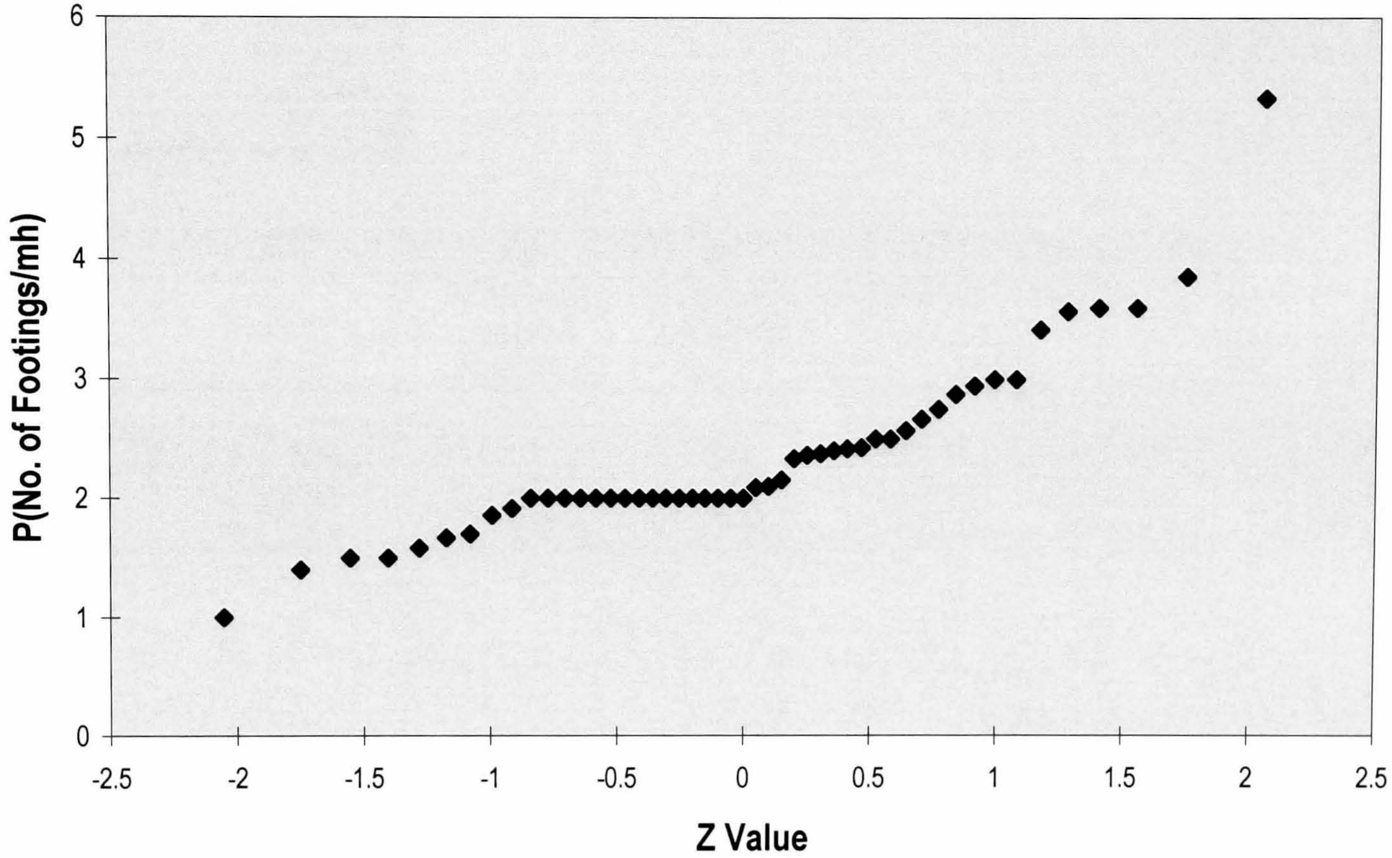
Micro-Level Productivity Data Collection Form
Reinforcing Steel

Date:	Project No.:	Form No.: S-1'
Element observed:		Element Mark:
Starting Time:	Finishing Time:	Delays:
Total No. of Fixers Worked to Complete the Activity:		

Setting-out Axes Productivity - Isolated Foundations					
Proj. No.	**P(No. of Footings/mh)**	**No. of Footings**	**No. of Axes**	**No. of Footings/No. of Axes**	**Input (mh)**
0202	2.43	17	12	1.42	7.00
0205	2.50	35	25	1.40	14.00
0206	2.57	36	29	1.24	14.00
0207	3.42	41	25	1.64	12.00
0208	2.00	12	12	1.00	6.00
0209	2.50	10	7	1.43	4.00
0210	1.00	9	14	0.64	9.00
0211	2.42	29	23	1.26	12.00
0211	2.33	35	28	1.25	15.00
0211	2.00	22	22	1.00	11.00
0211	1.58	19	22	0.86	12.00
0301	1.67	5	7	0.71	3.00
0303	3.60	36	20	1.80	10.00
0304	1.50	3	4	0.75	2.00
0306	1.50	9	11	0.82	6.00
0307	3.57	50	29	1.72	14.00
0310	2.38	19	13	1.46	8.00
0311	3.00	12	8	1.50	4.00
0312	3.60	18	9	2.00	5.00
0313	2.94	53	35	1.51	18.00
0314	2.67	16	11	1.45	6.00
0316	2.00	26	25	1.04	13.00
0317	1.70	17	21	0.81	10.00
0318	2.00	4	4	1.00	2.00
0319	5.33	48	14	3.43	9.00

Setting-out Axes Productivity - Isolated Foundations					
Proj. No.	**P(No. of Footings/mh)**	**No. of Footings**	**No. of Axes**	**No. of Footings/No. of Axes**	**Input (mh)**
0320	2.15	28	27	1.04	13.00
0321	2.36	52	38	1.37	22.00
0322	2.88	23	14	1.64	8.00
0323	1.40	14	17	0.82	10.00
0324	2.00	3	4	0.75	1.50
0325	2.00	14	14	1.00	7.00
0326	2.75	33	22	1.50	12.00
0326	3.00	33	22	1.50	11.00
0202(Annex)	2.40	6	5	1.20	2.50
0309-a	2.00	6	5	1.20	3.00
0309-b	2.00	4	4	1.00	2.00
0309-b	2.00	4	4	1.00	2.00
0309-c	2.00	4	4	1.00	2.00
0309-c	2.00	4	4	1.00	2.00
0309-c	2.00	4	4	1.00	2.00
0309-c	2.00	4	4	1.00	2.00
0309-c	2.00	4	4	1.00	2.00
0309-c	2.00	4	4	1.00	2.00
0327-26	3.86	54	25	2.16	14.00
0327-27	1.92	23	21	1.10	12.00
0327-30	1.86	13	12	1.08	7.00
0327-32	2.09	23	19	1.21	11.00
0327-34	2.00	24	20	1.20	12.00
0327-37	2.10	42	36	1.17	20.00

Normal Probability Plot
Labour Productivity



Axes Setting-out Productivity - Isolated Foundations

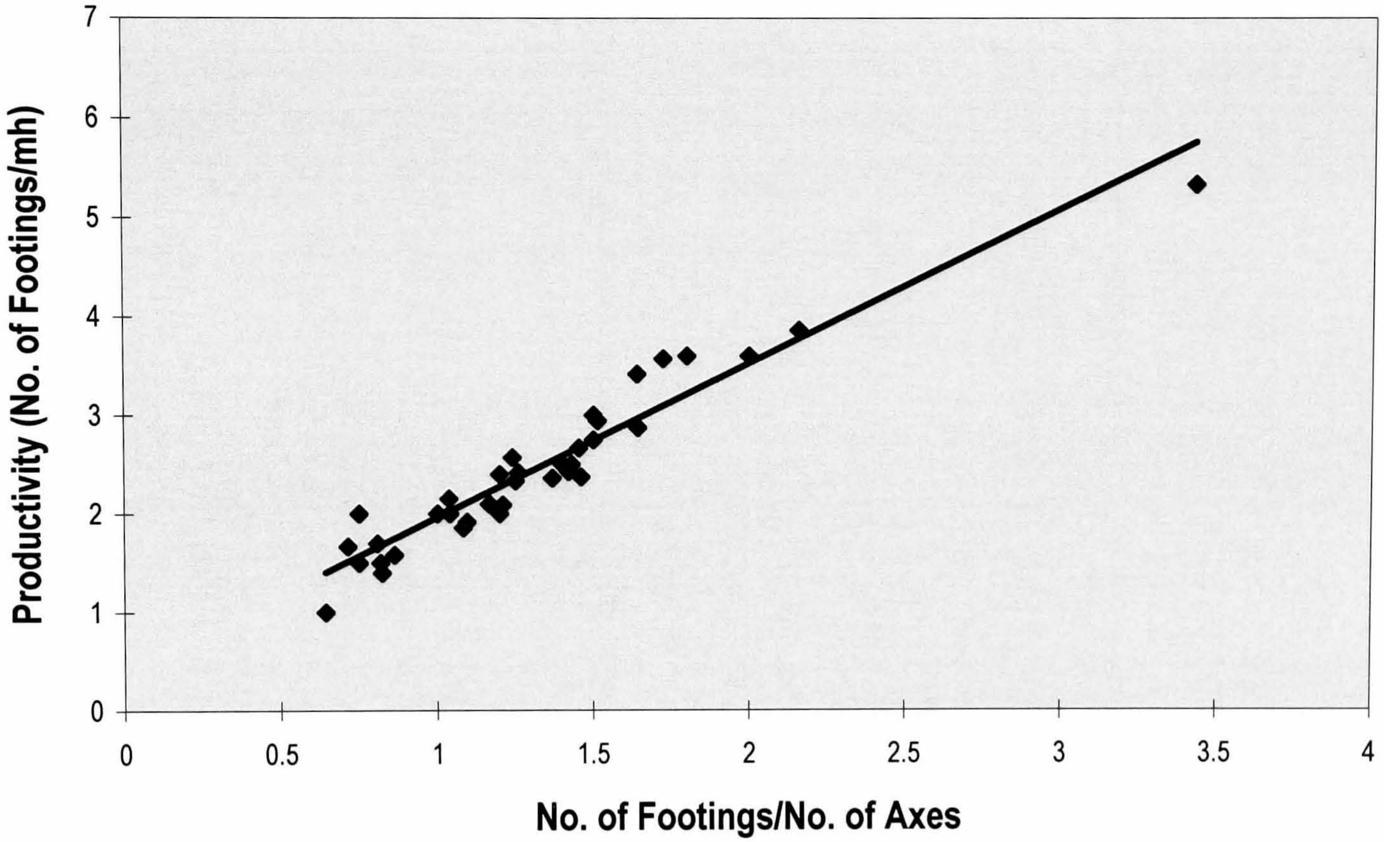
Regression Statistics	
Multiple R	0.961018186
R Square	0.923555954
Adjusted R Square	0.921929485
Standard Error	0.209439267
Observations	49

ANOVA

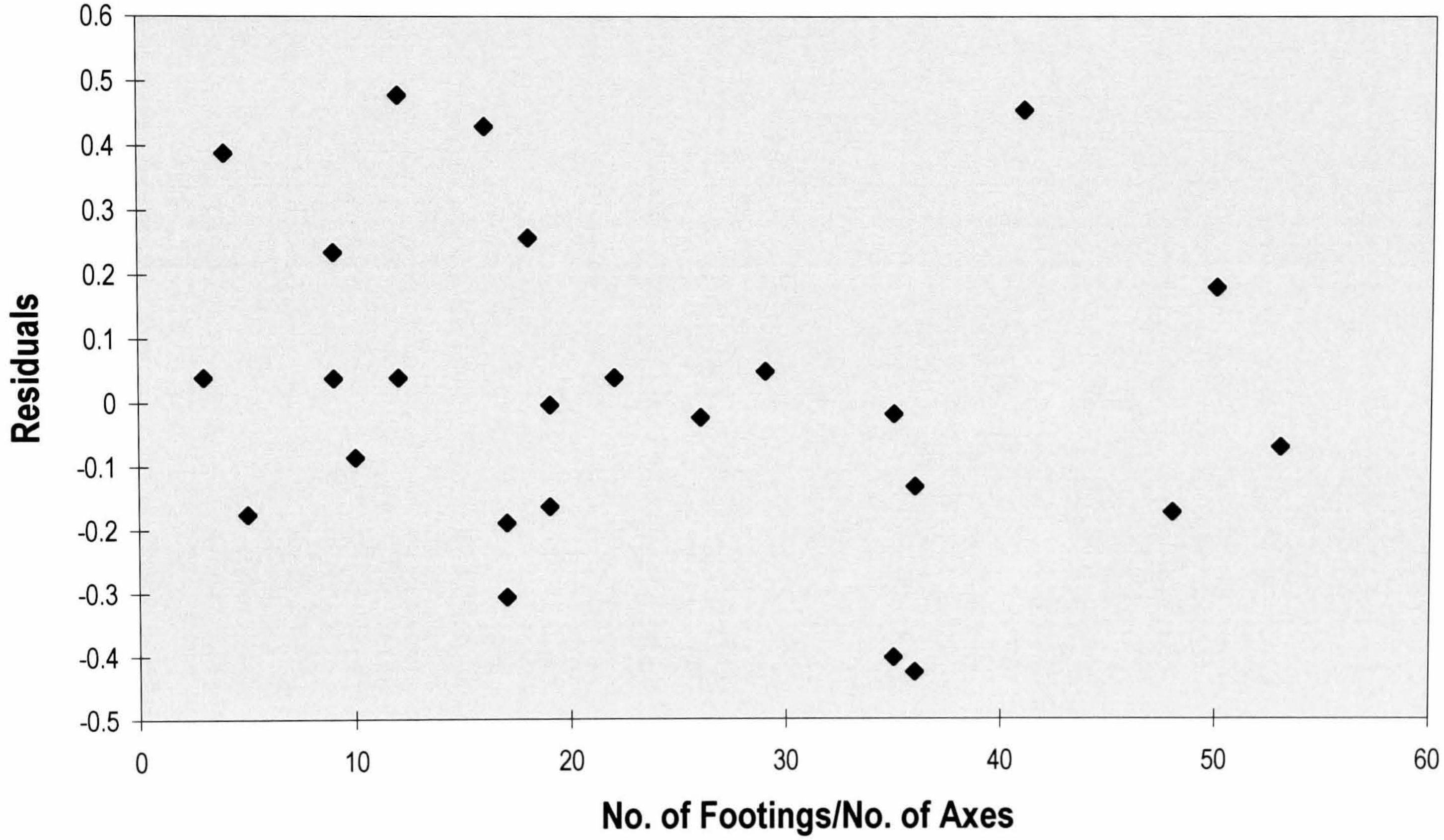
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	24.90769965	24.90769965	567.8287835	6.89755E-28
Residual	47	2.0616459	0.043864806		
Total	48	26.96934555			

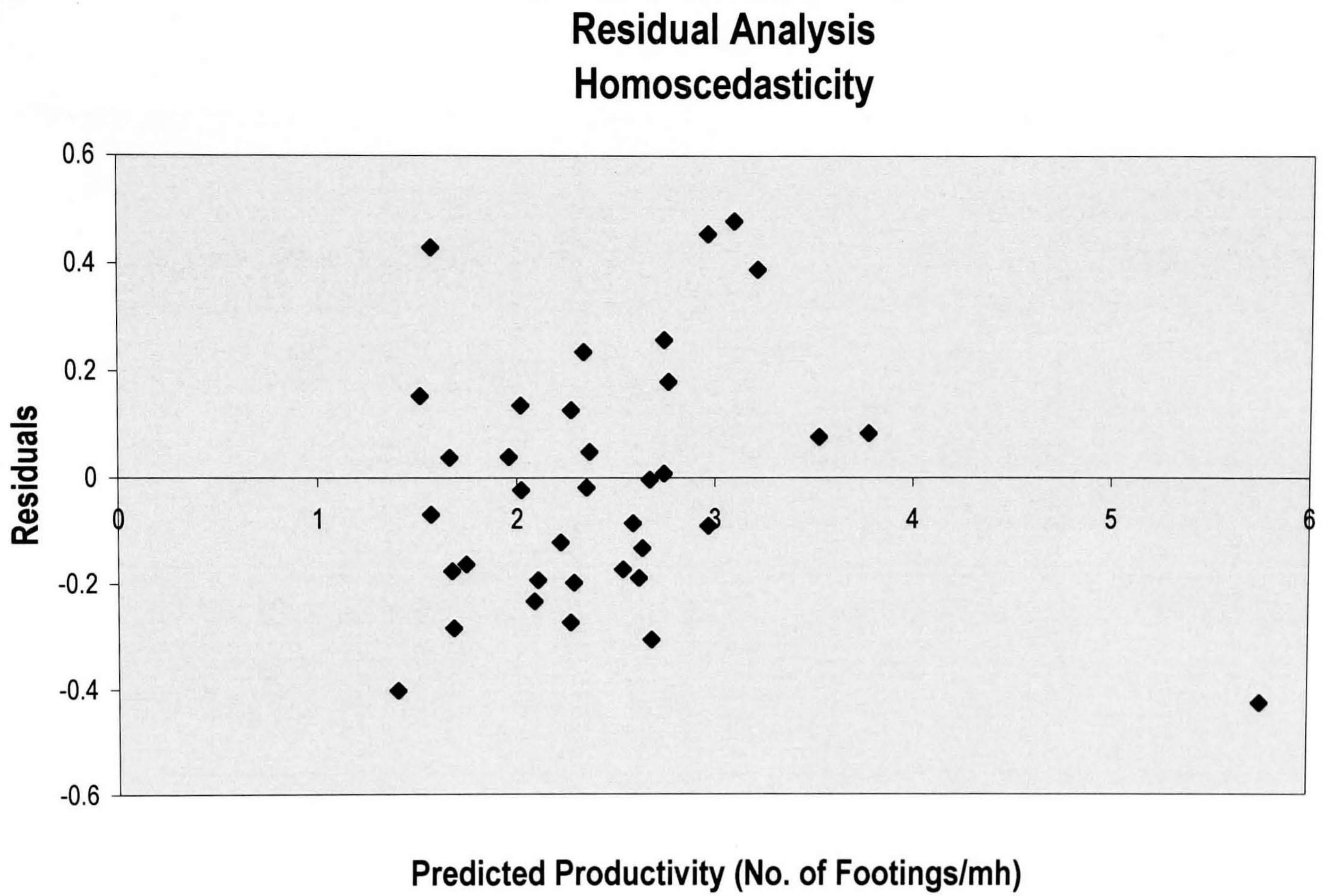
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.397250807	0.087091871	4.561284564	3.64372E-05	0.222044727	0.572456887
No. of Footings/No. of Axes	1.563141784	0.06559786	23.82915826	6.89755E-28	1.431176036	1.695107532

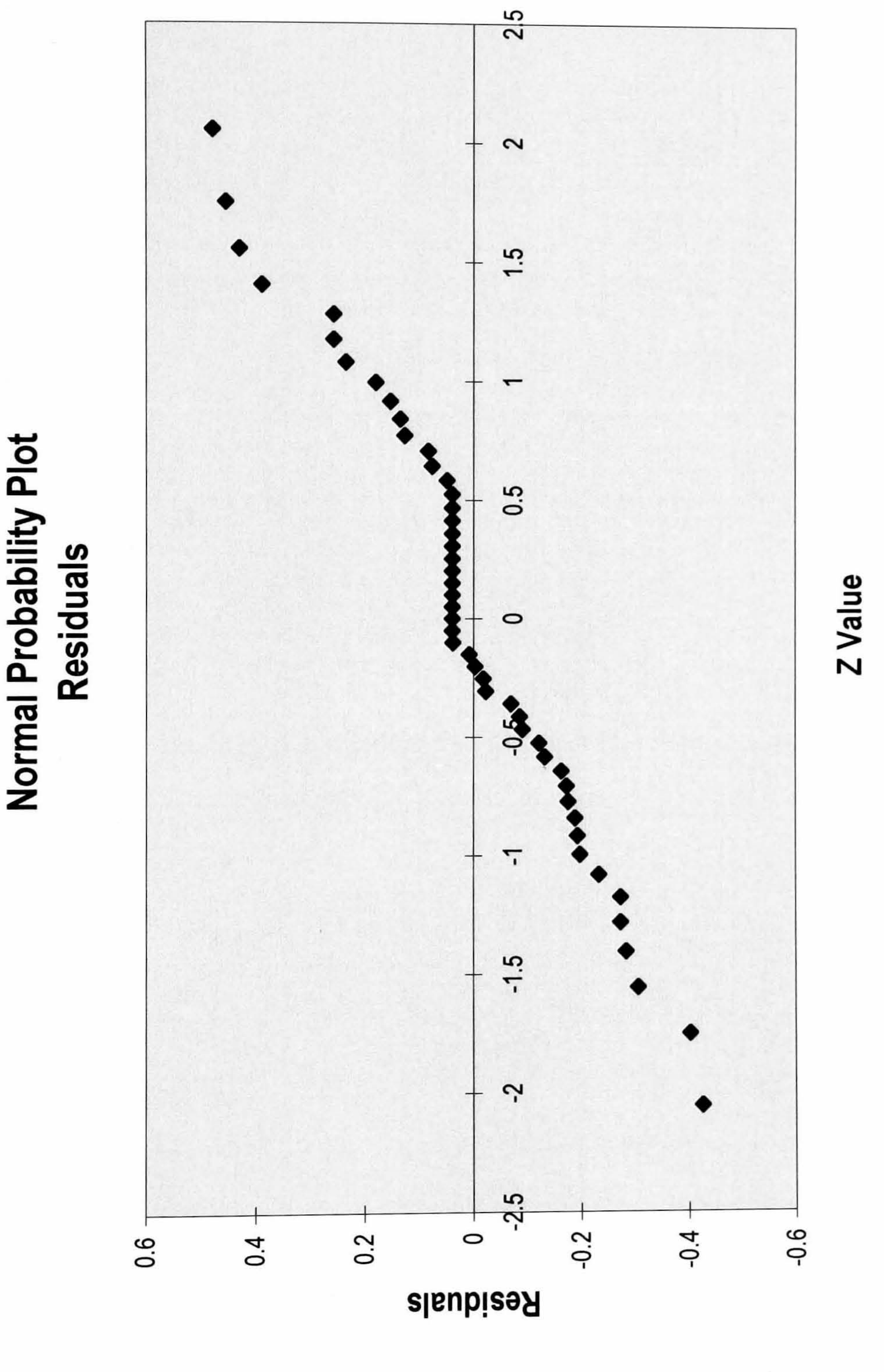
Axes Setting-out Productivity
Isolated Foundations



Residual Analysis
Zero Mean Error




Residual Analysis
Homoscedasticity
Residuals
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
1
2
3
4
5
6
Predicted Productivity (No. of Footings/mh)


Normal Probability Plot
Residuals
Residuals
Z Value
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5